Searching for Perfect Fluidity in a Cold Atomic Gas

John E. Thomas

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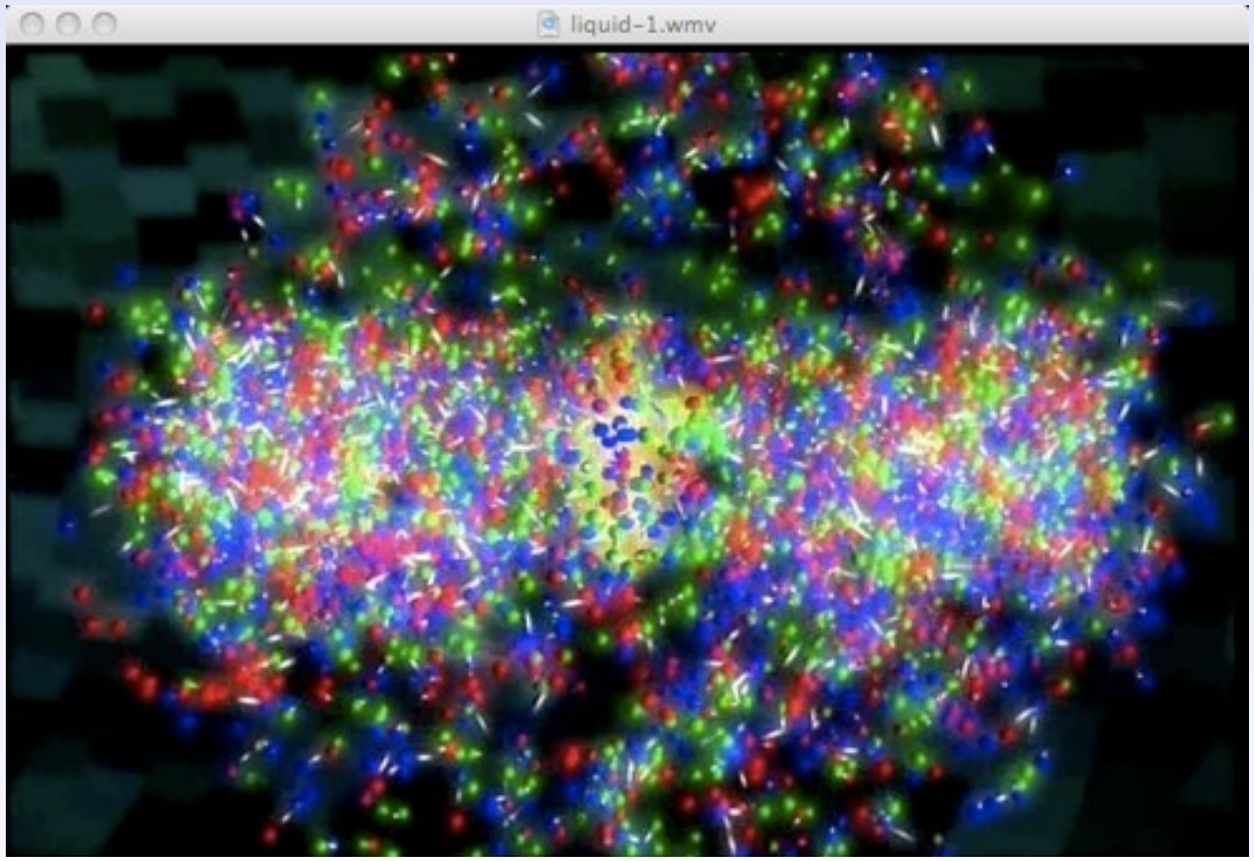

Quark-gluon plasma $T = 10^{12}$ K

Computer simulation of RHIC collision

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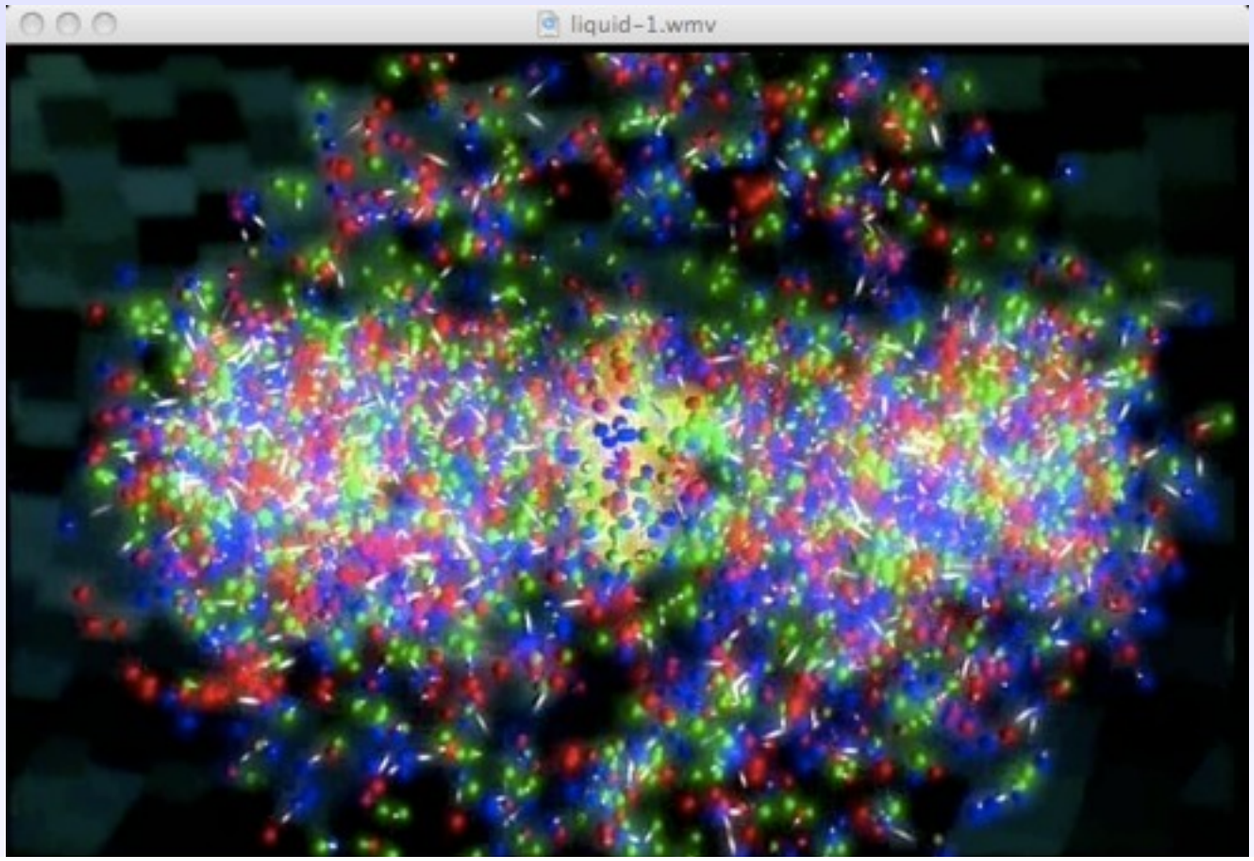
"JETLAB" Group

Duke Physics

Atom Cooling and Trapping



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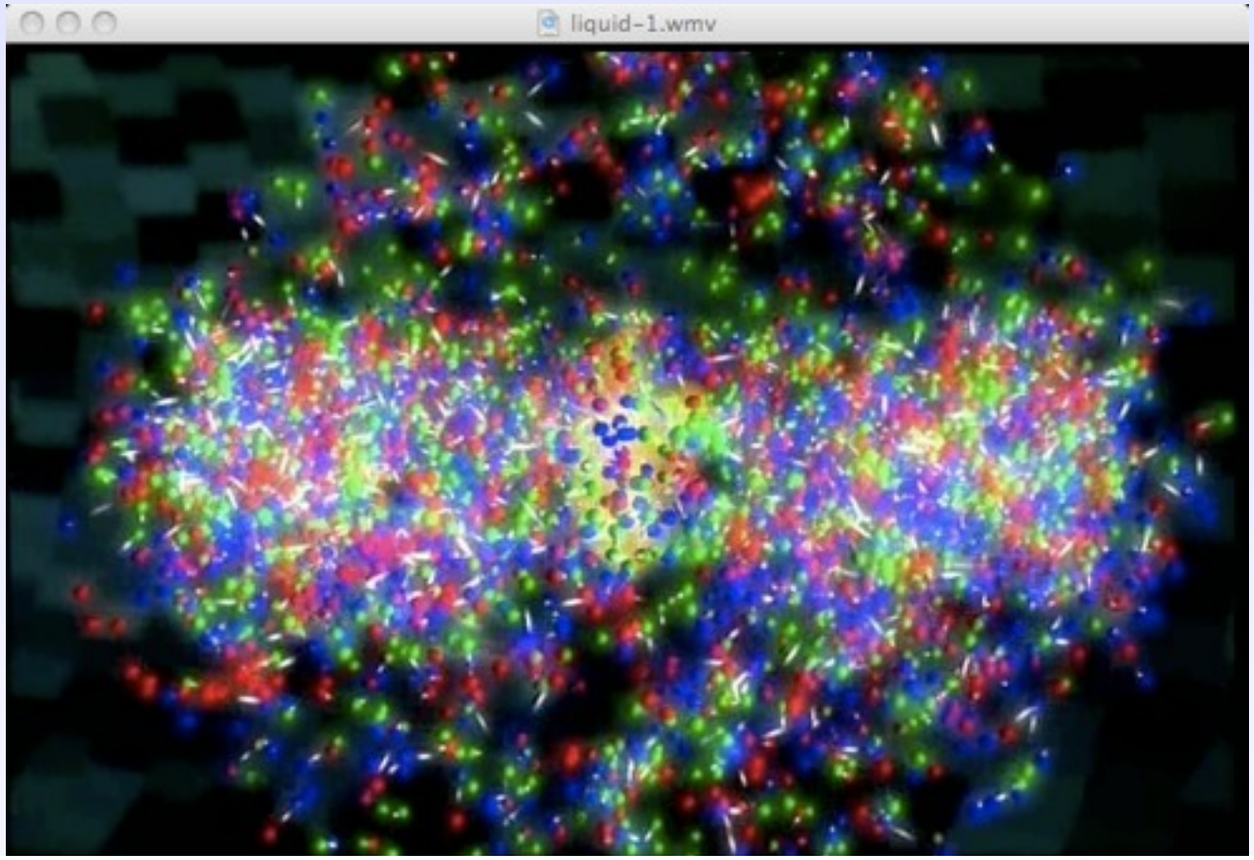

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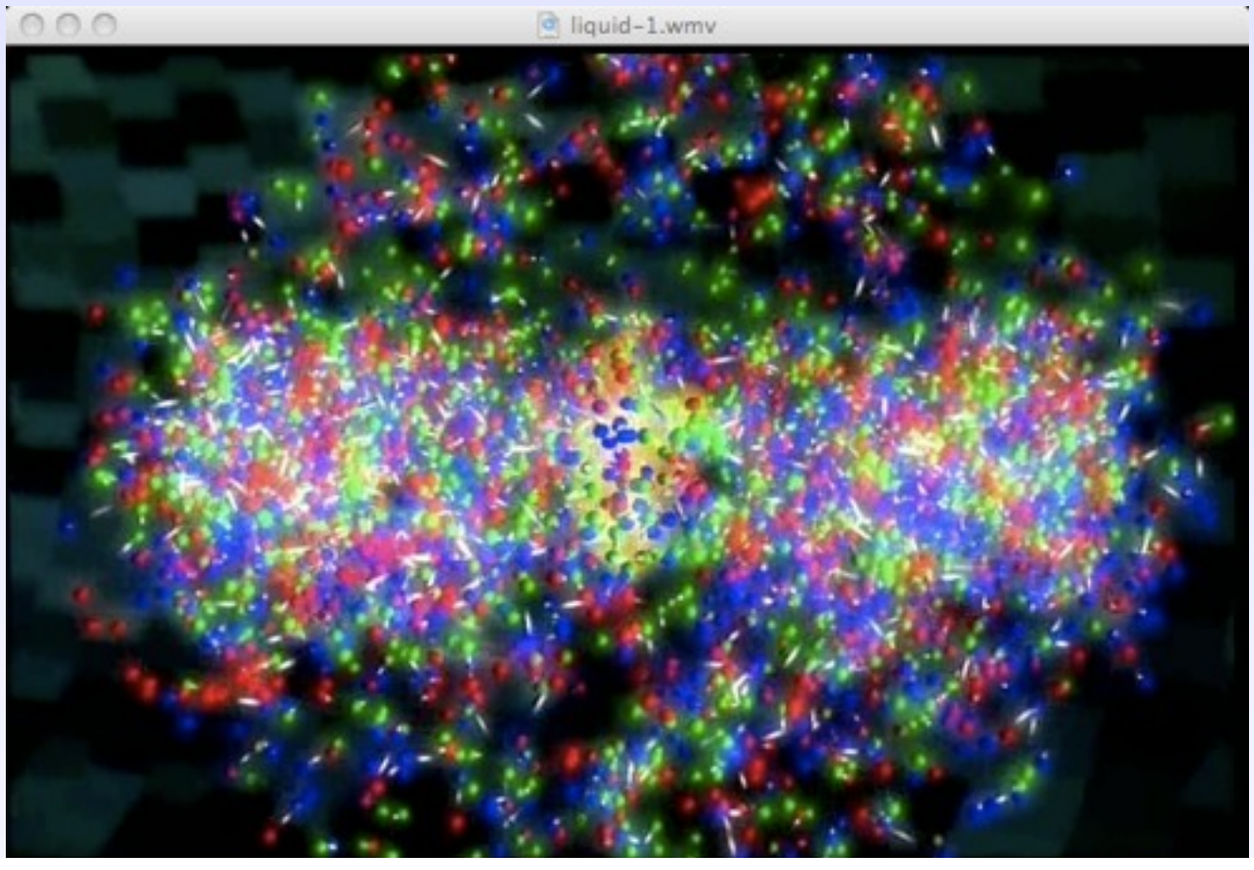

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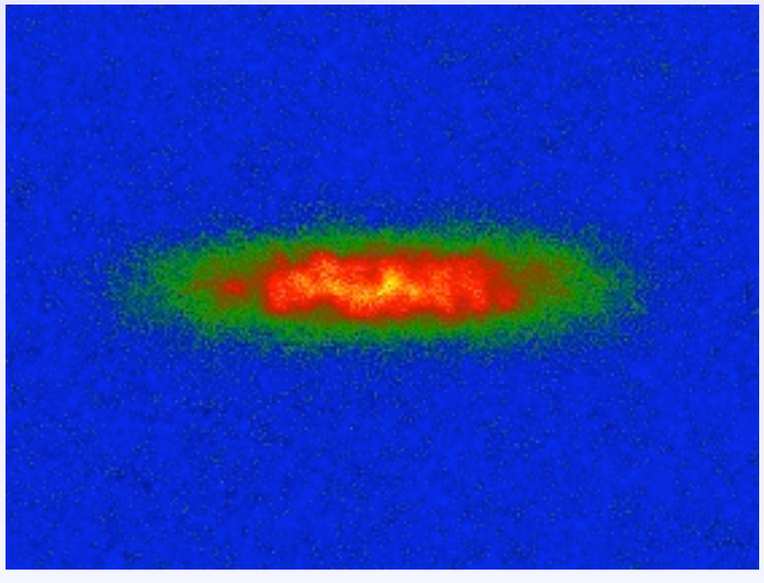


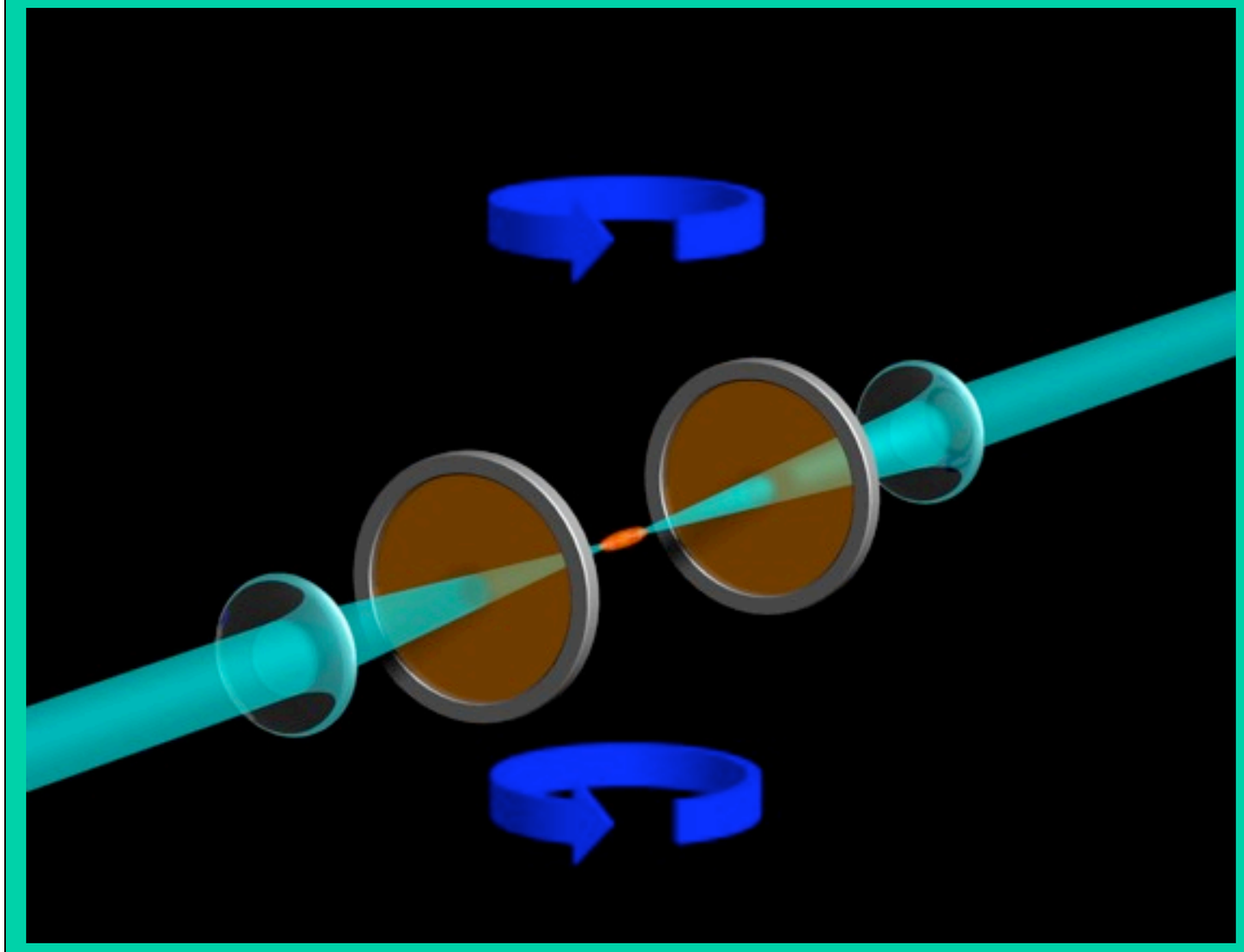
Ultracold atomic gas

$T = 10^{-7}$ K

Optical Traps –Bowls made of Light

Duke Physics

Atom Cooling and Trapping



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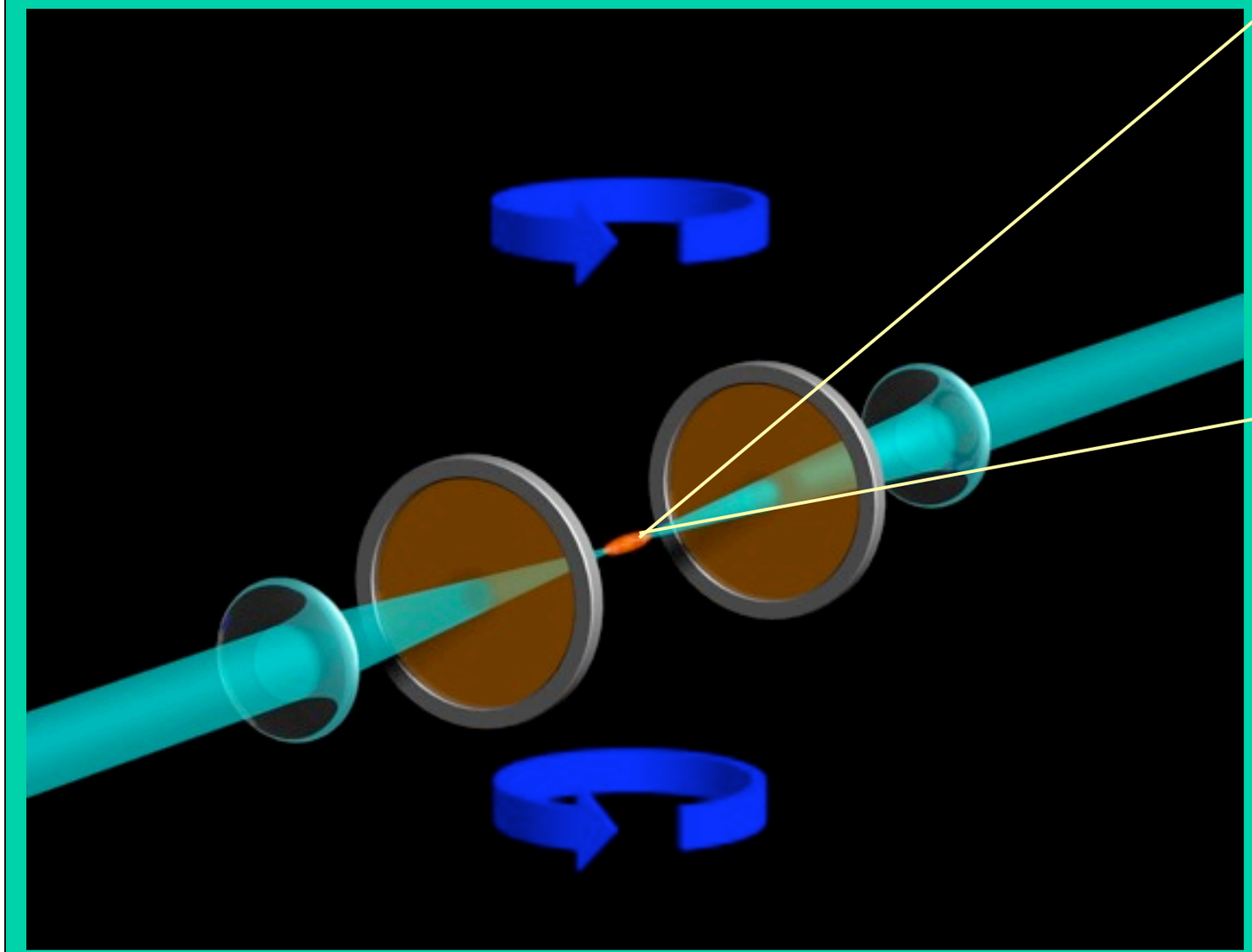
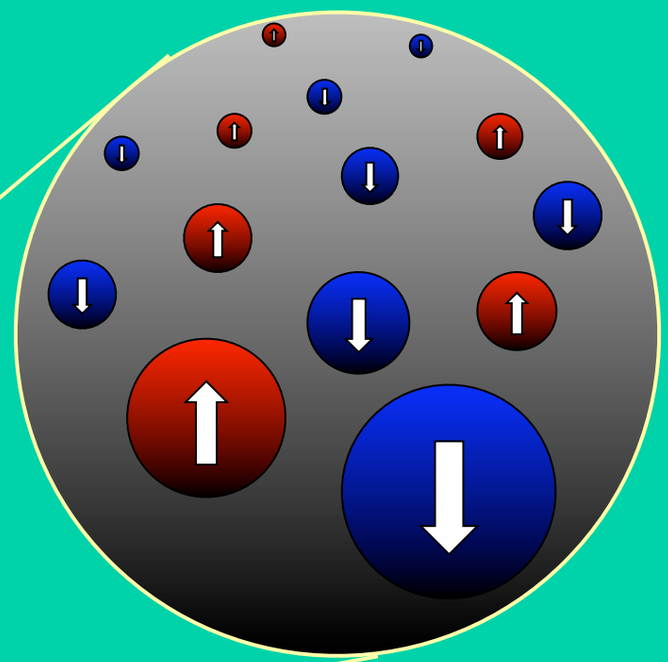
Atom Cooling and Trapping

Our atom: ^{6}Li





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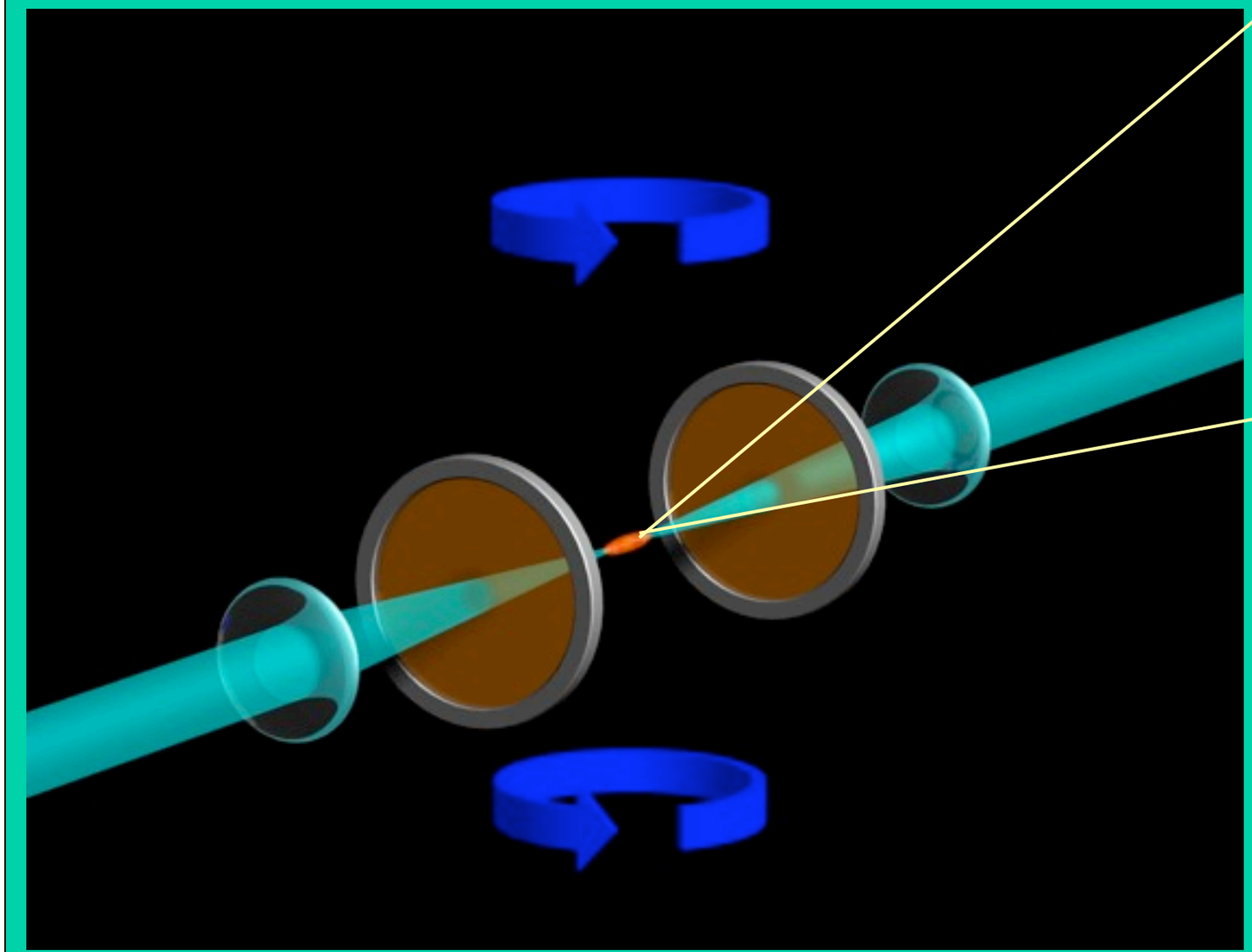

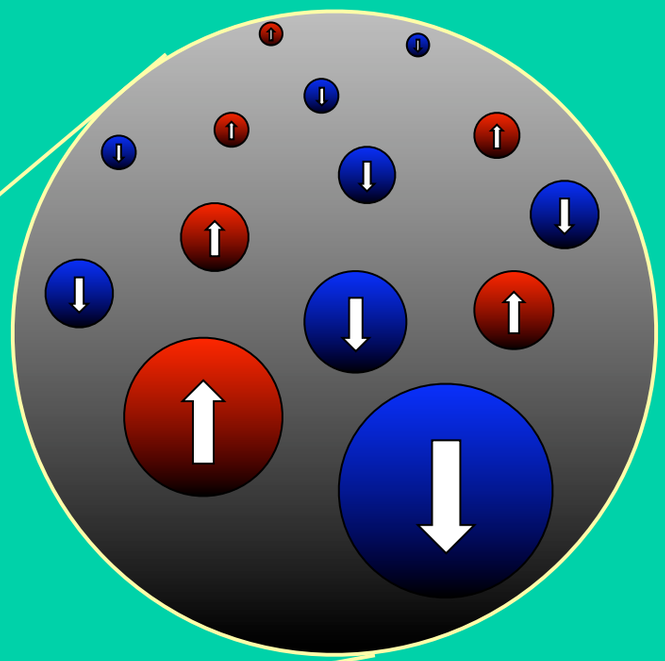

Mixture of
Spin–up and Spin–down
(like *electrons—fermions*)

Optical Traps –Bowls made of Light

Duke Physics

Atom Cooling and Trapping

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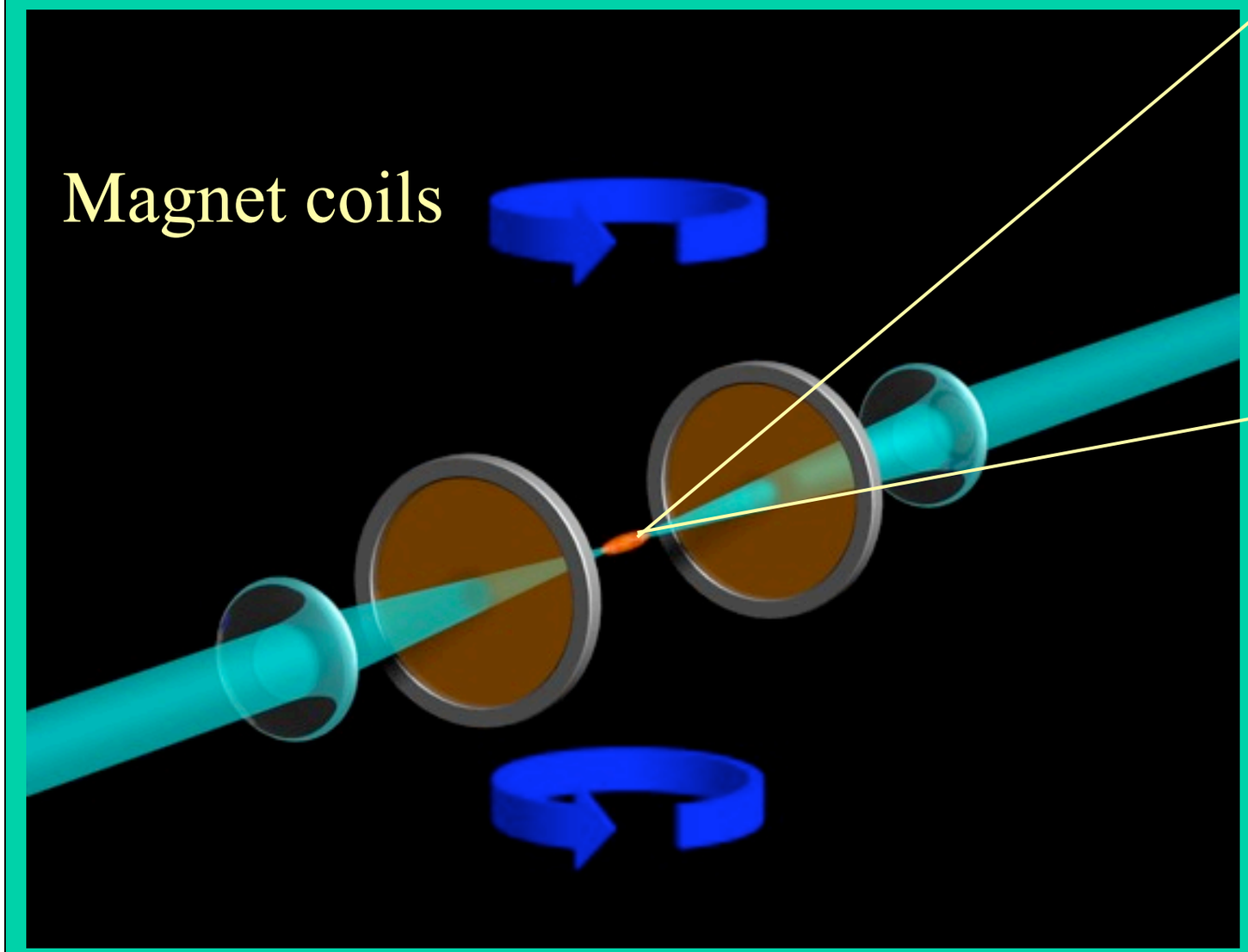

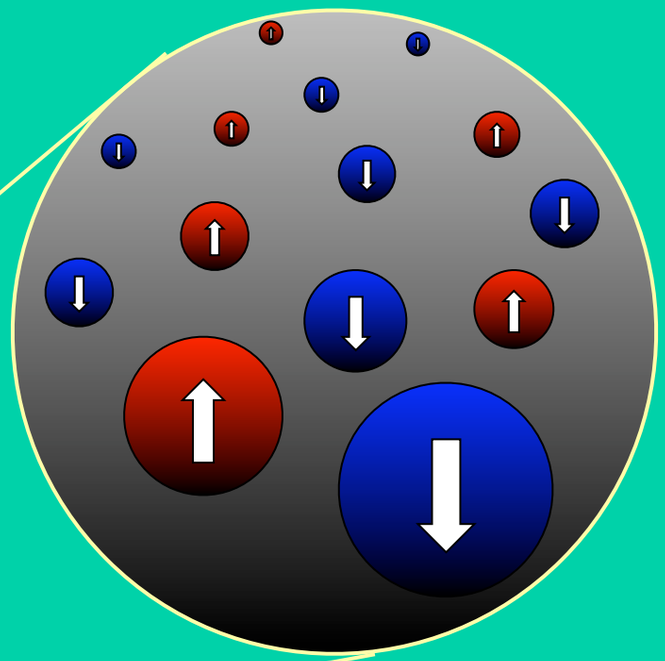

Mixture of
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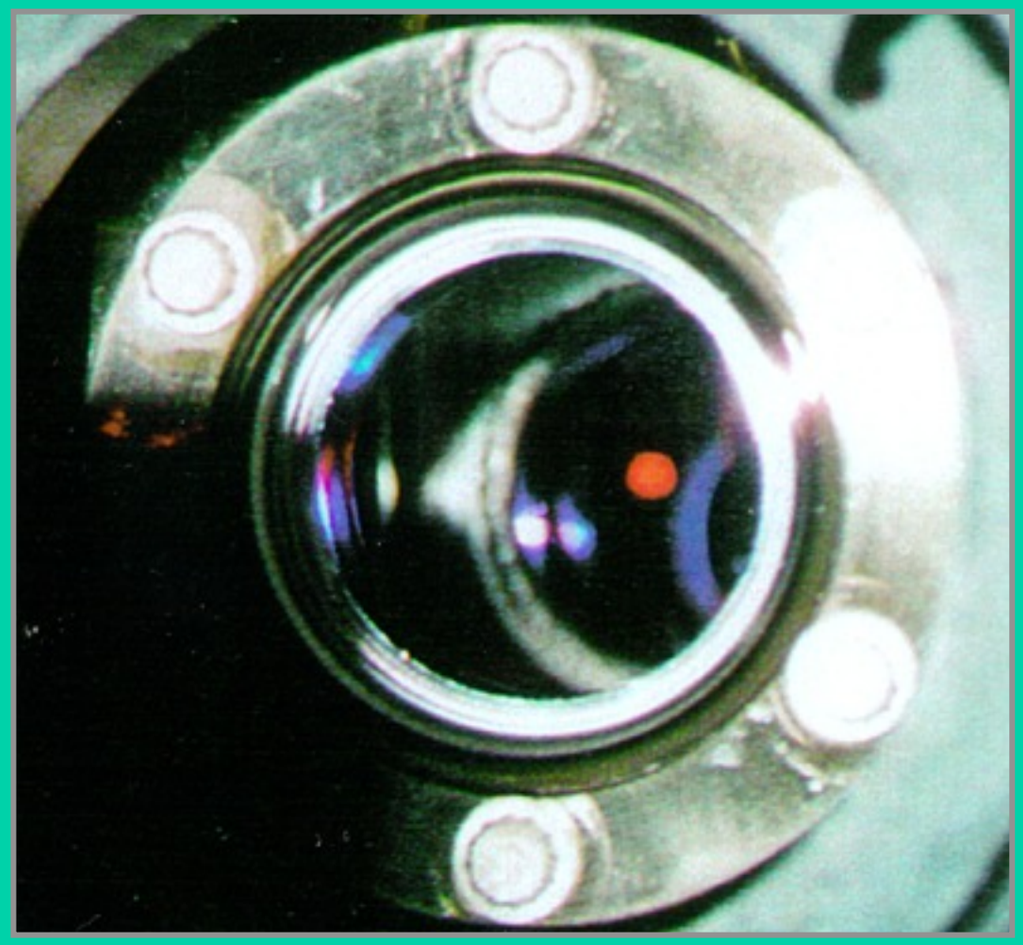
Preparation of an Ultracold ^{6}Li gas

Duke Physics

Atom Cooling and Trapping



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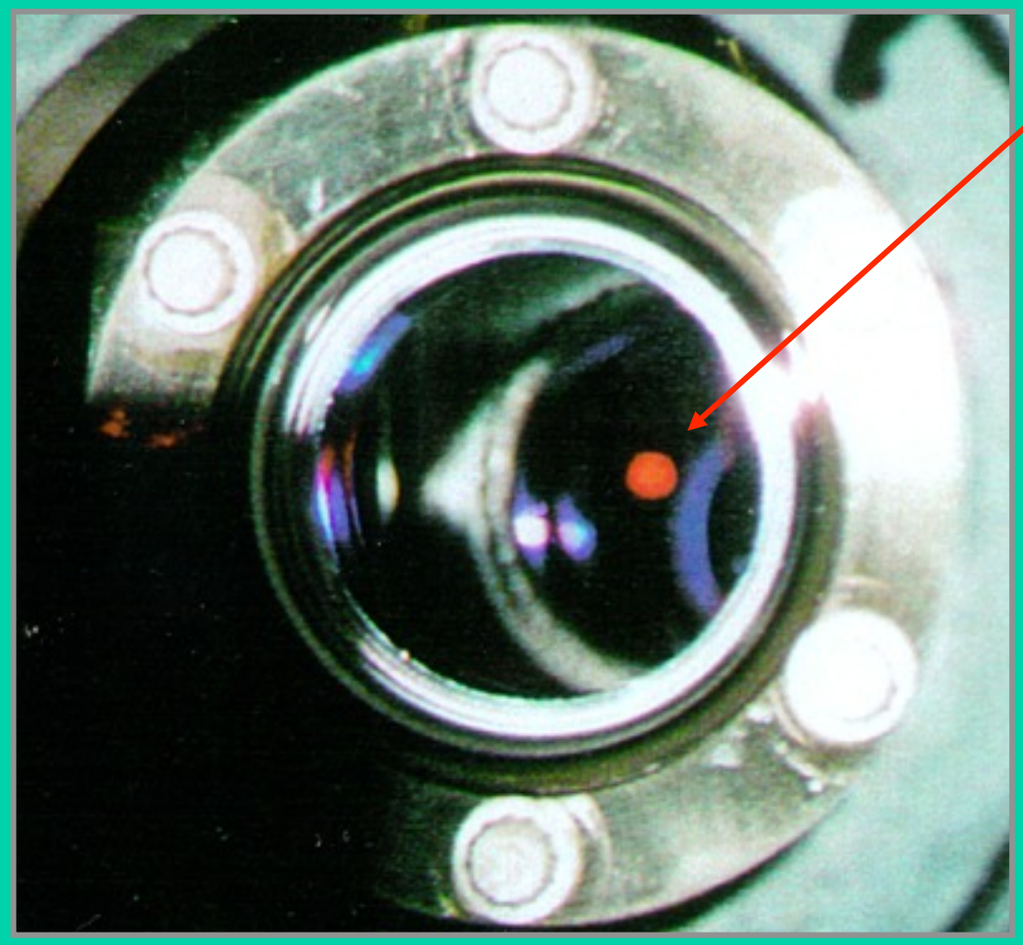

Atoms precooled to 150 μK

Preparation of an Ultracold ^{6}Li gas

Duke Physics
Atom Cooling and Trapping

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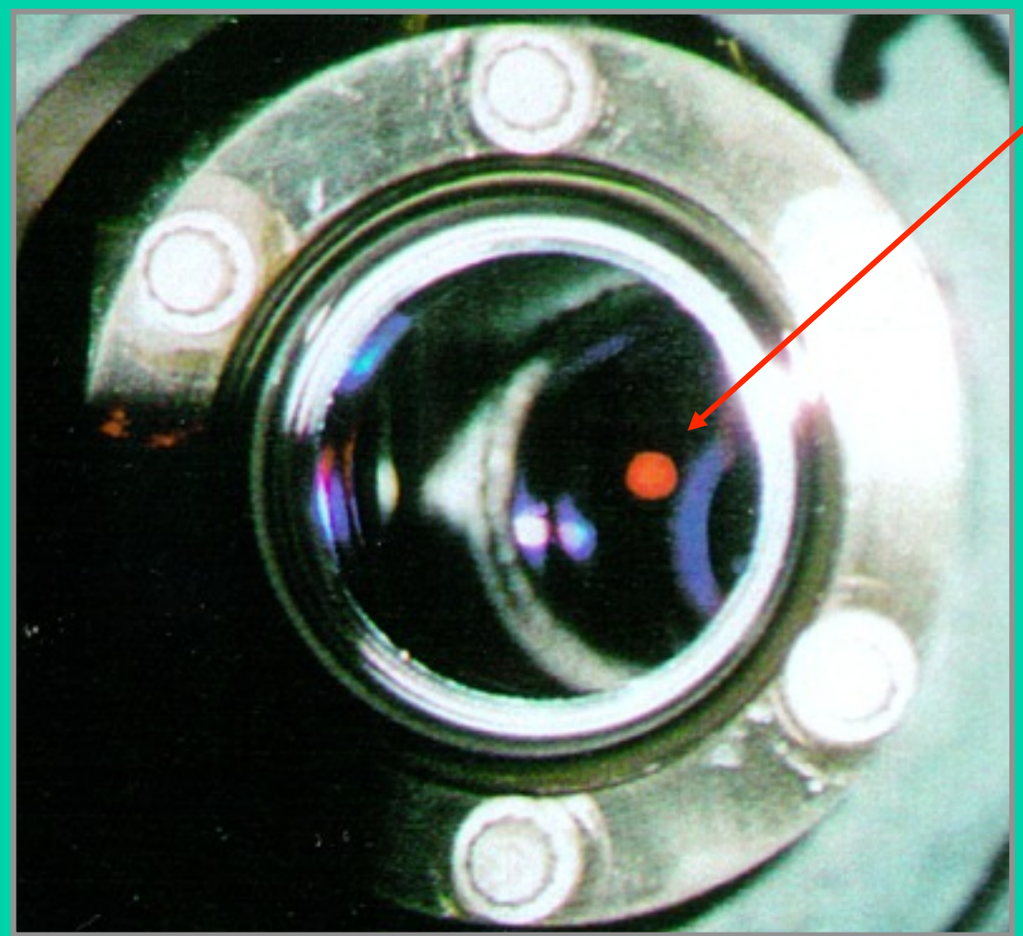
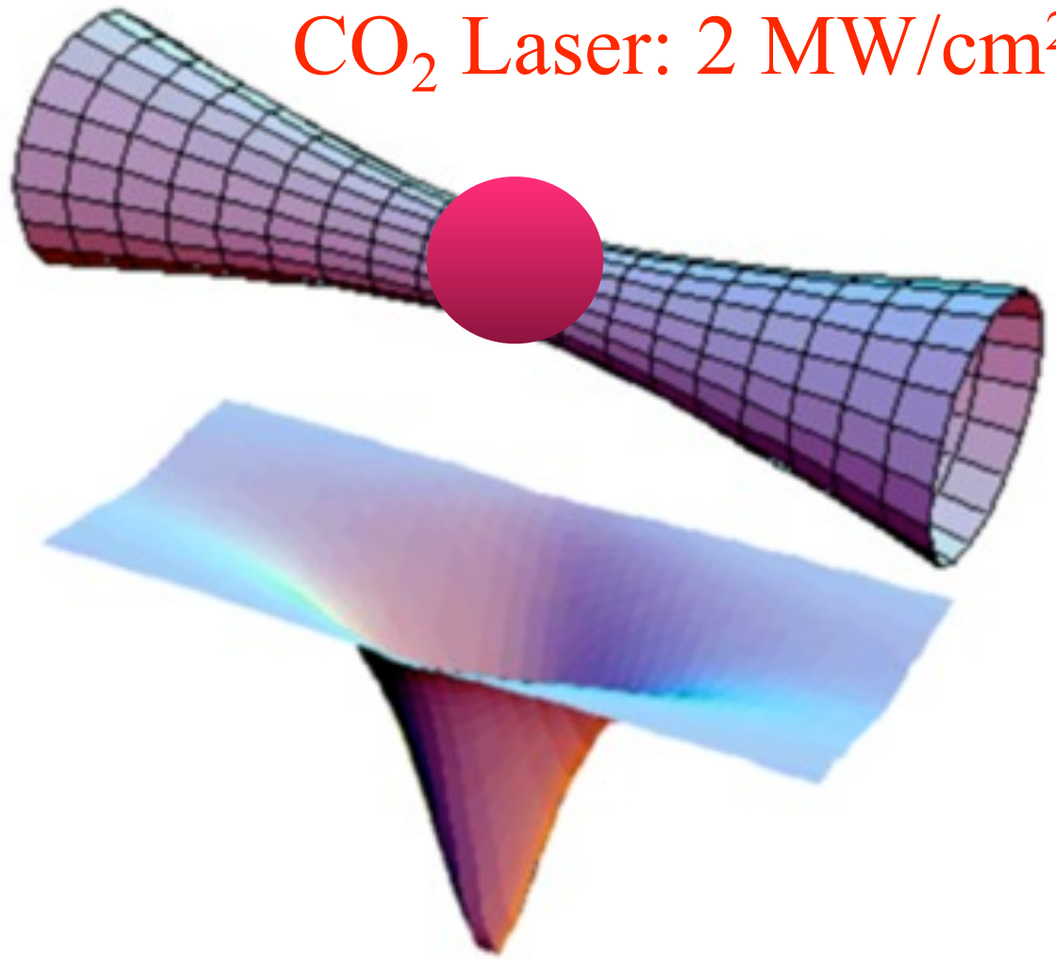


CO_2 Laser: 2 MW/cm^2



CO_2 Laser Beam

Duke Physics

Atom Cooling and Trapping

CO_2 Laser Beam

Duke Physics

Atom Cooling and Trapping

Stable Commercial Laser

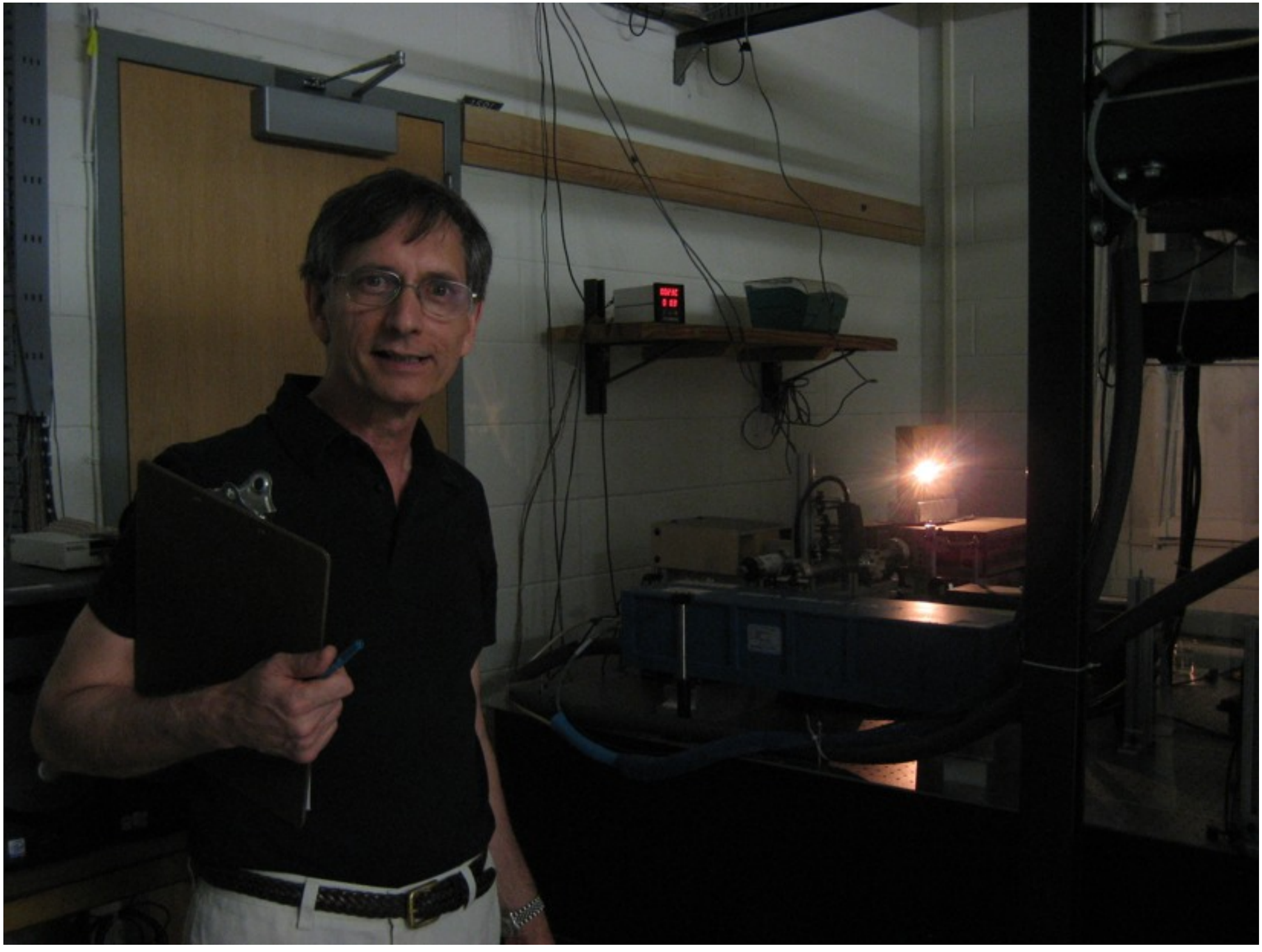
140 Watt CO_2 Laser

Invisible infrared beam $\lambda = 10.6\ \mu m$

CO_2 Laser Beam

Duke Physics

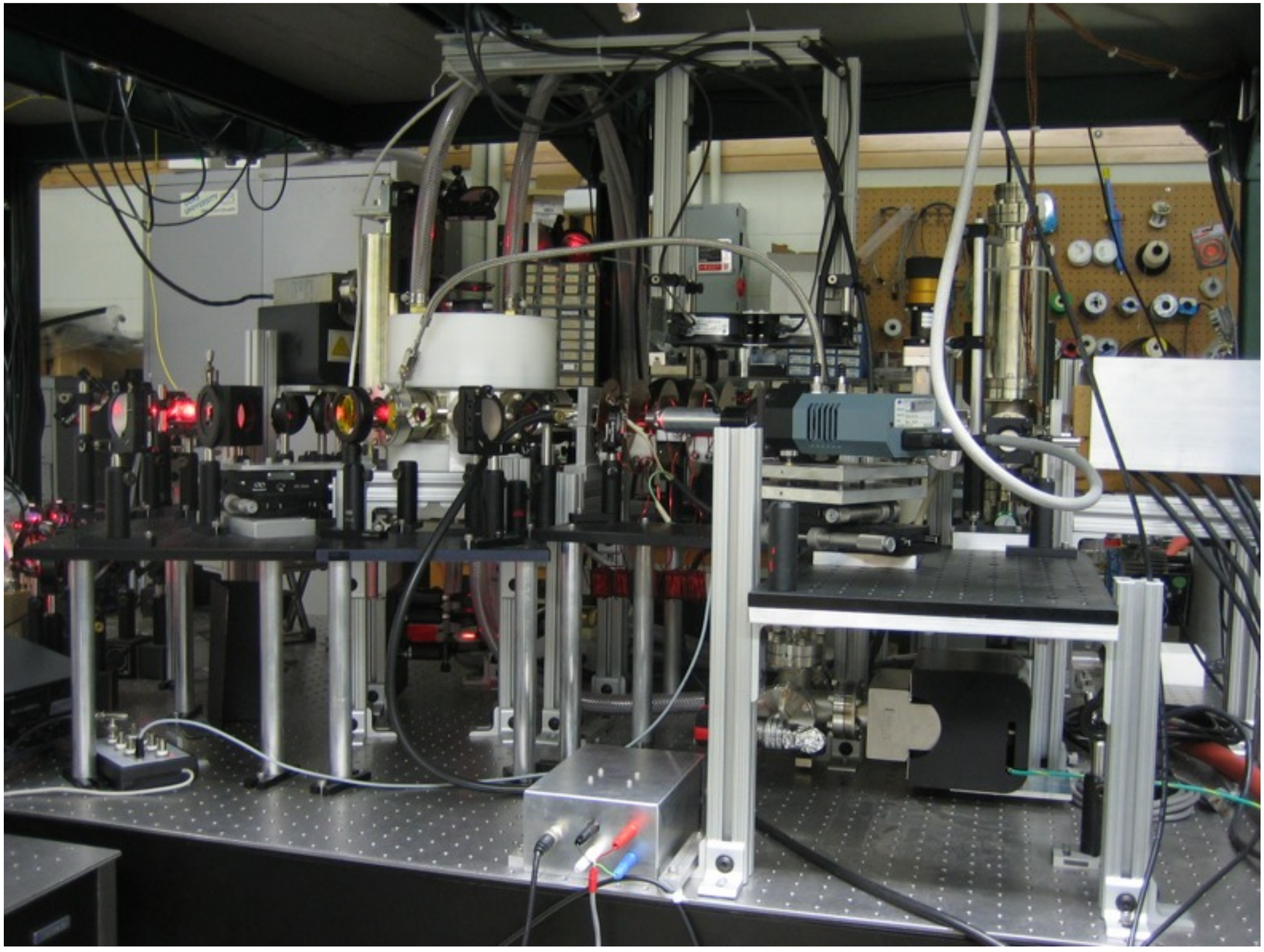
Atom Cooling and Trapping



Experimental Apparatus

Duke Physics

Atom Cooling and Trapping



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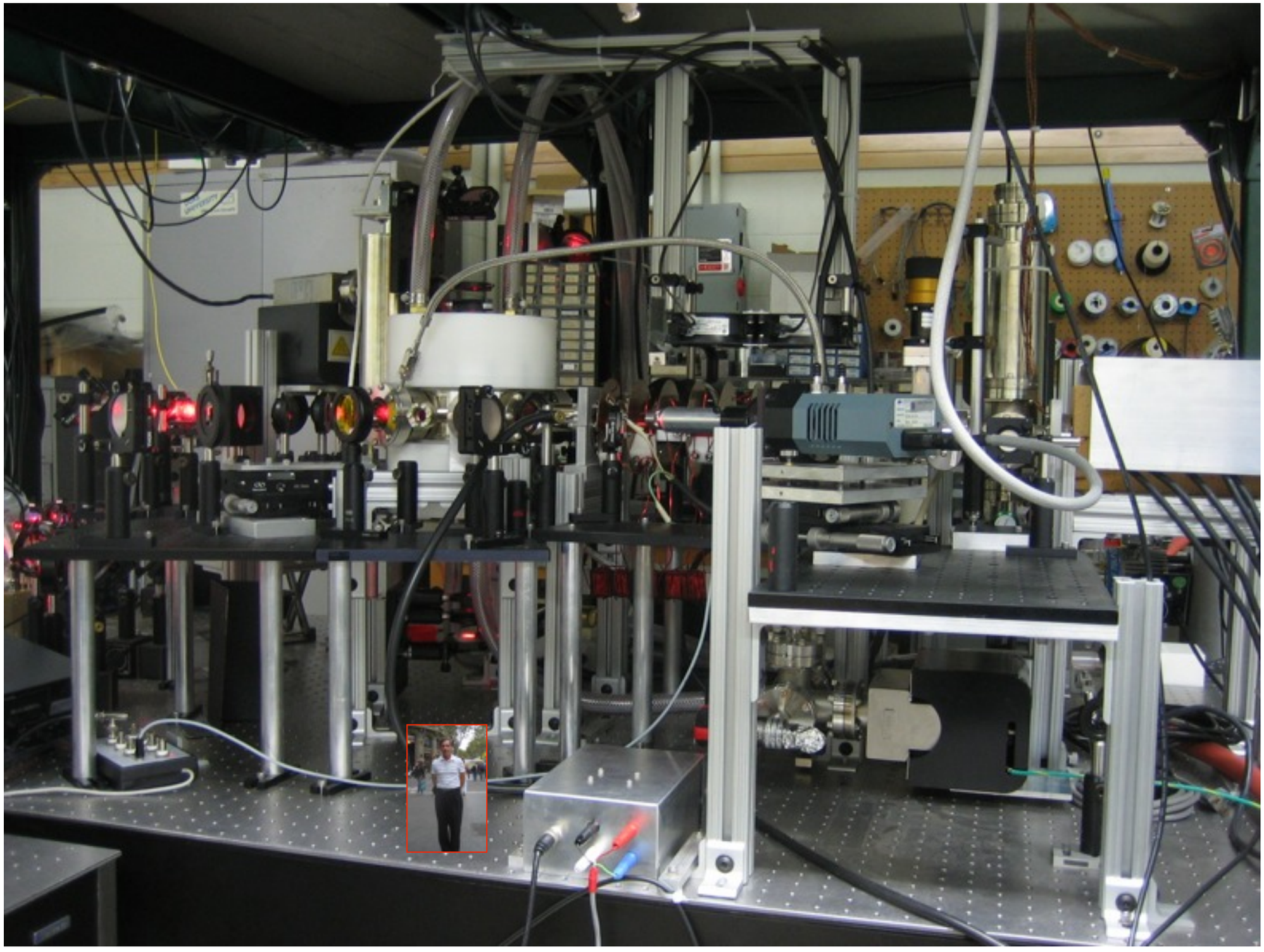

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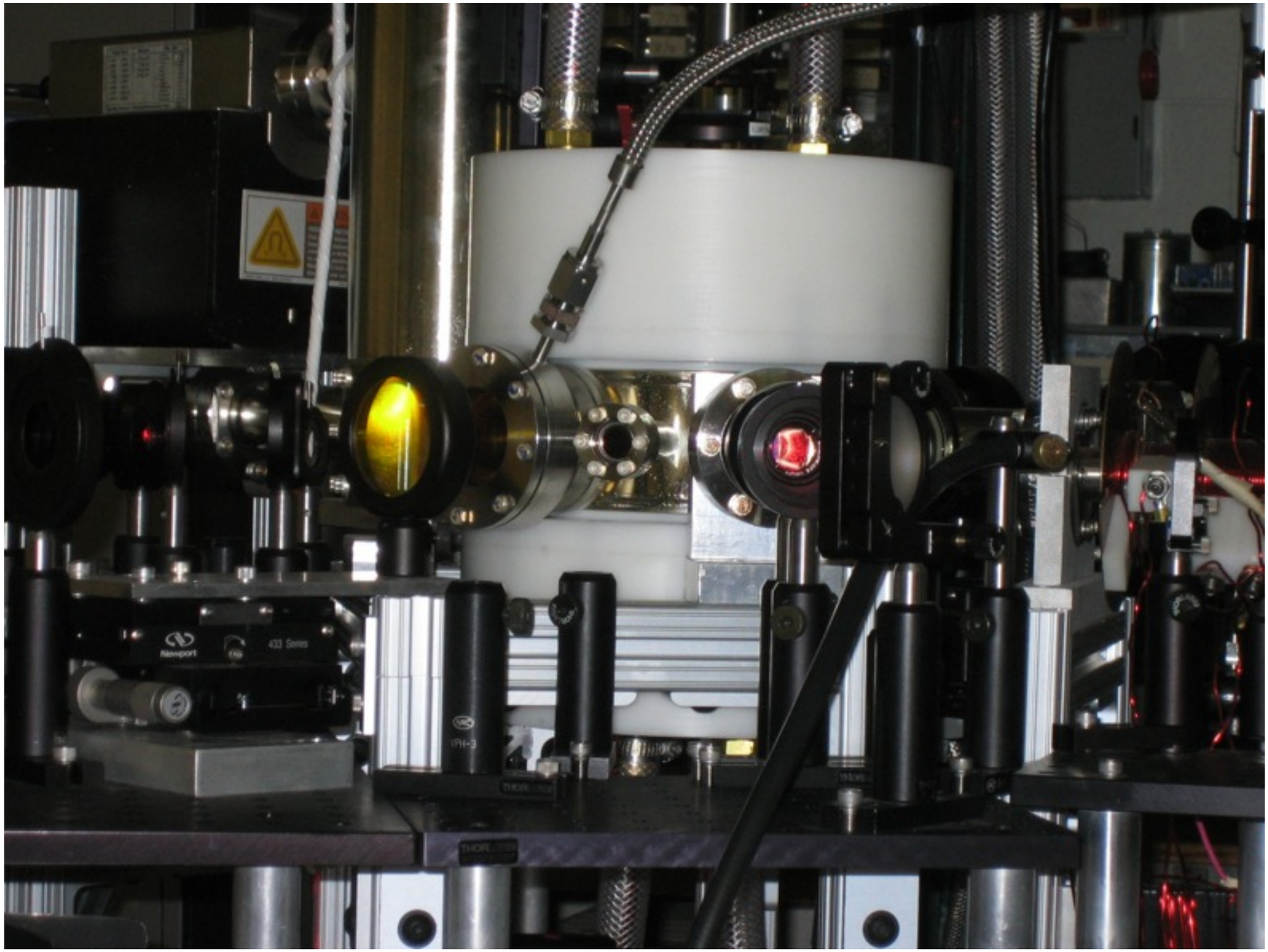

Tunable Strong Repulsion and Attraction

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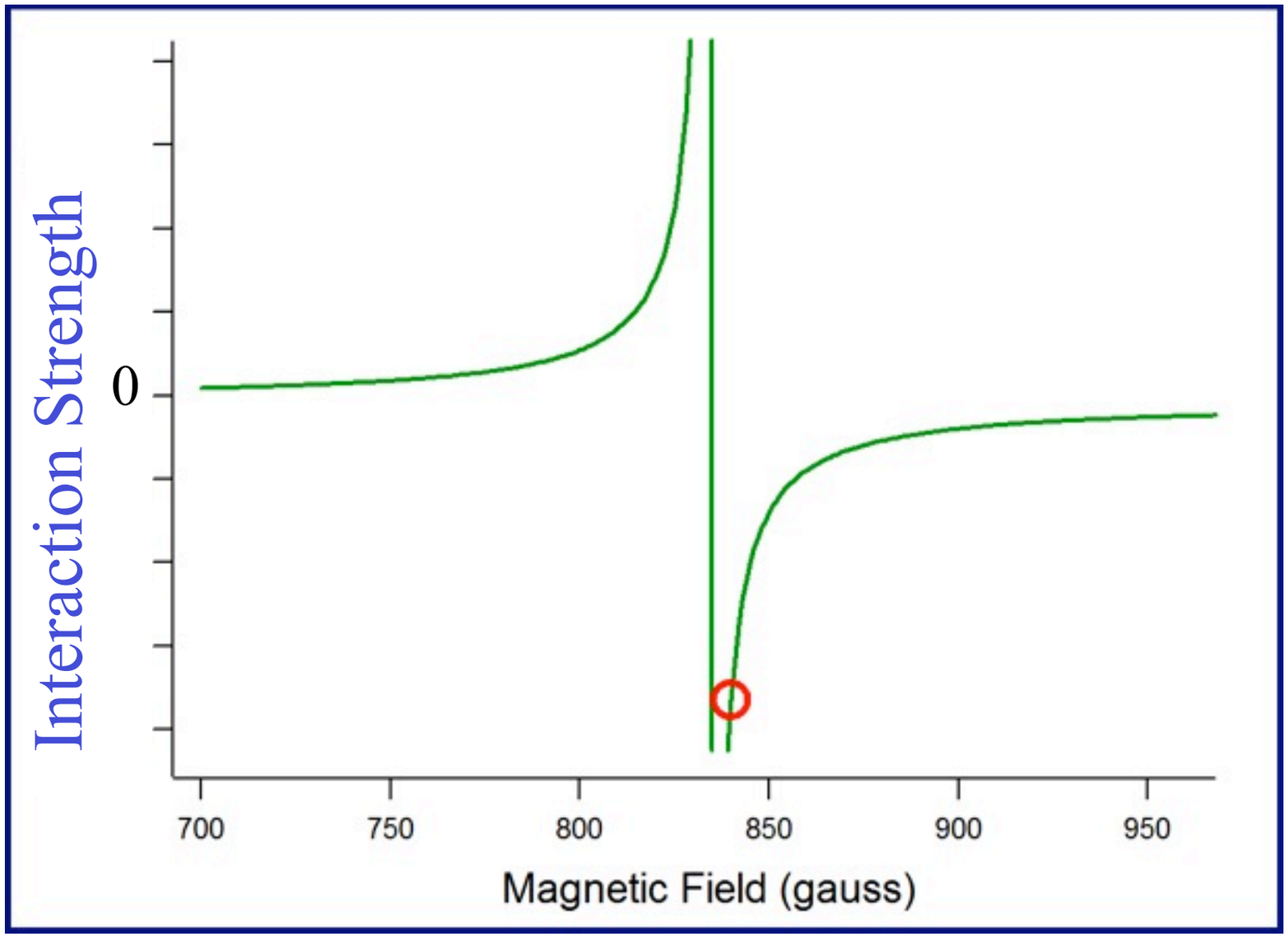

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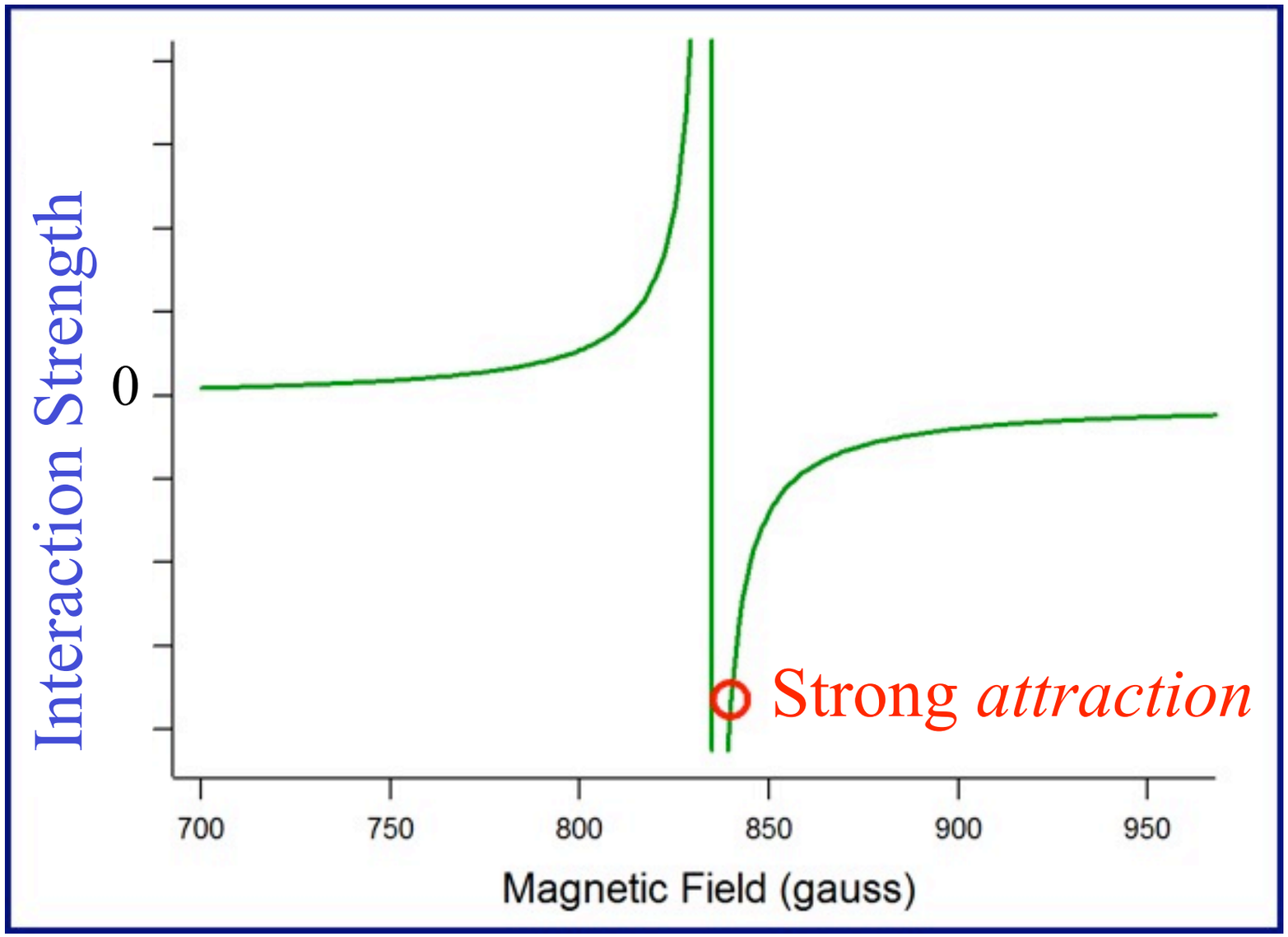

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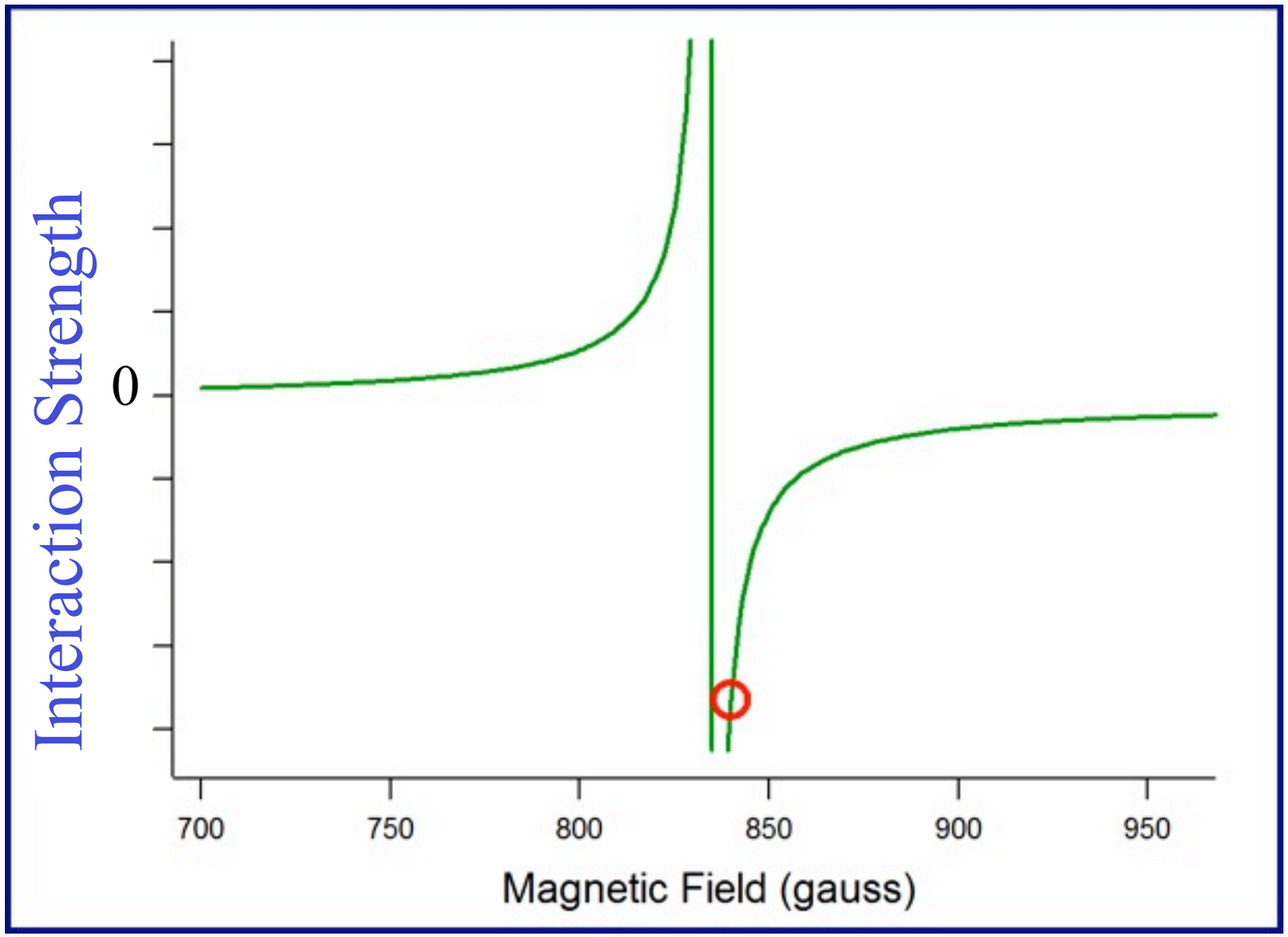

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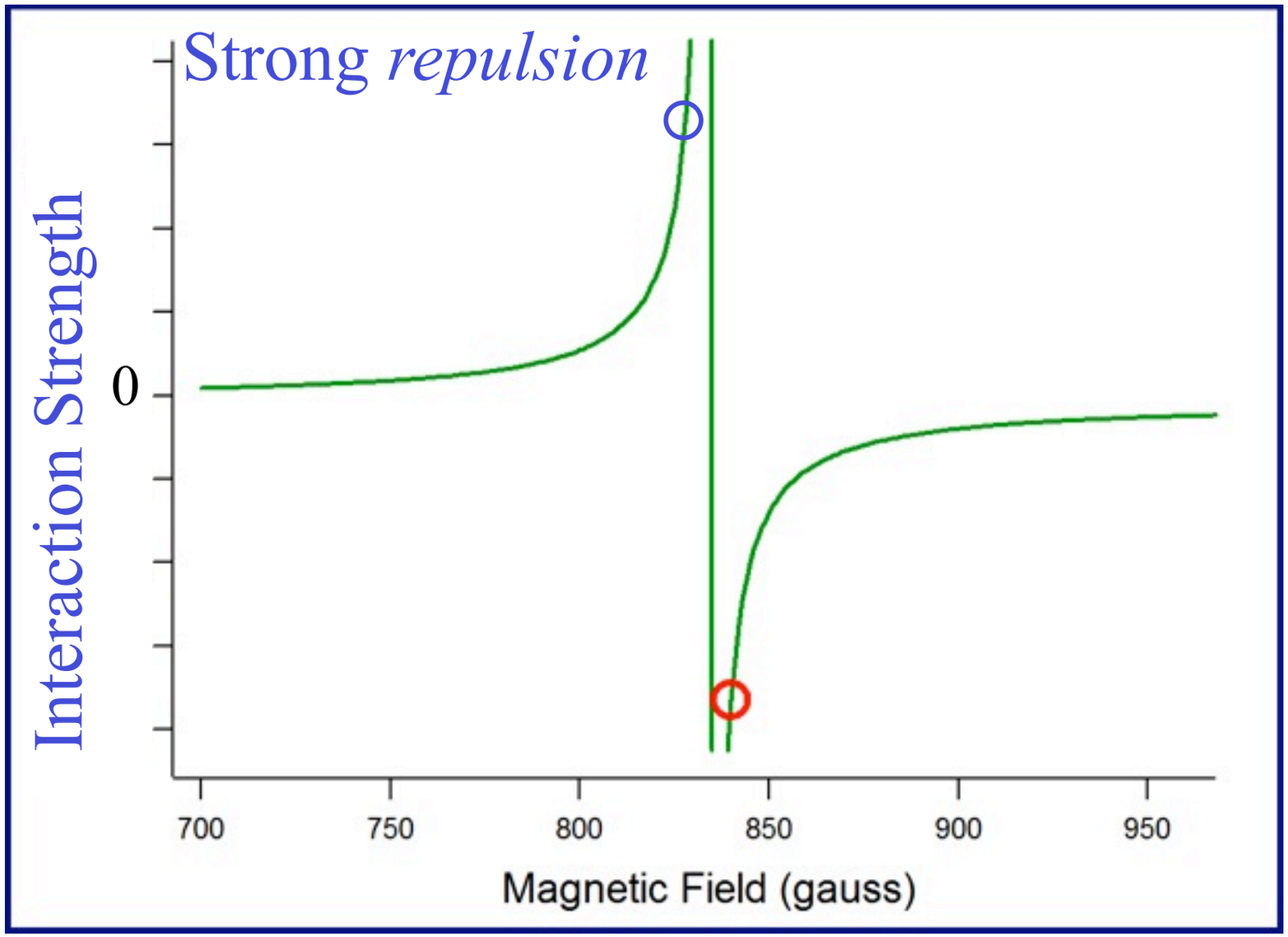

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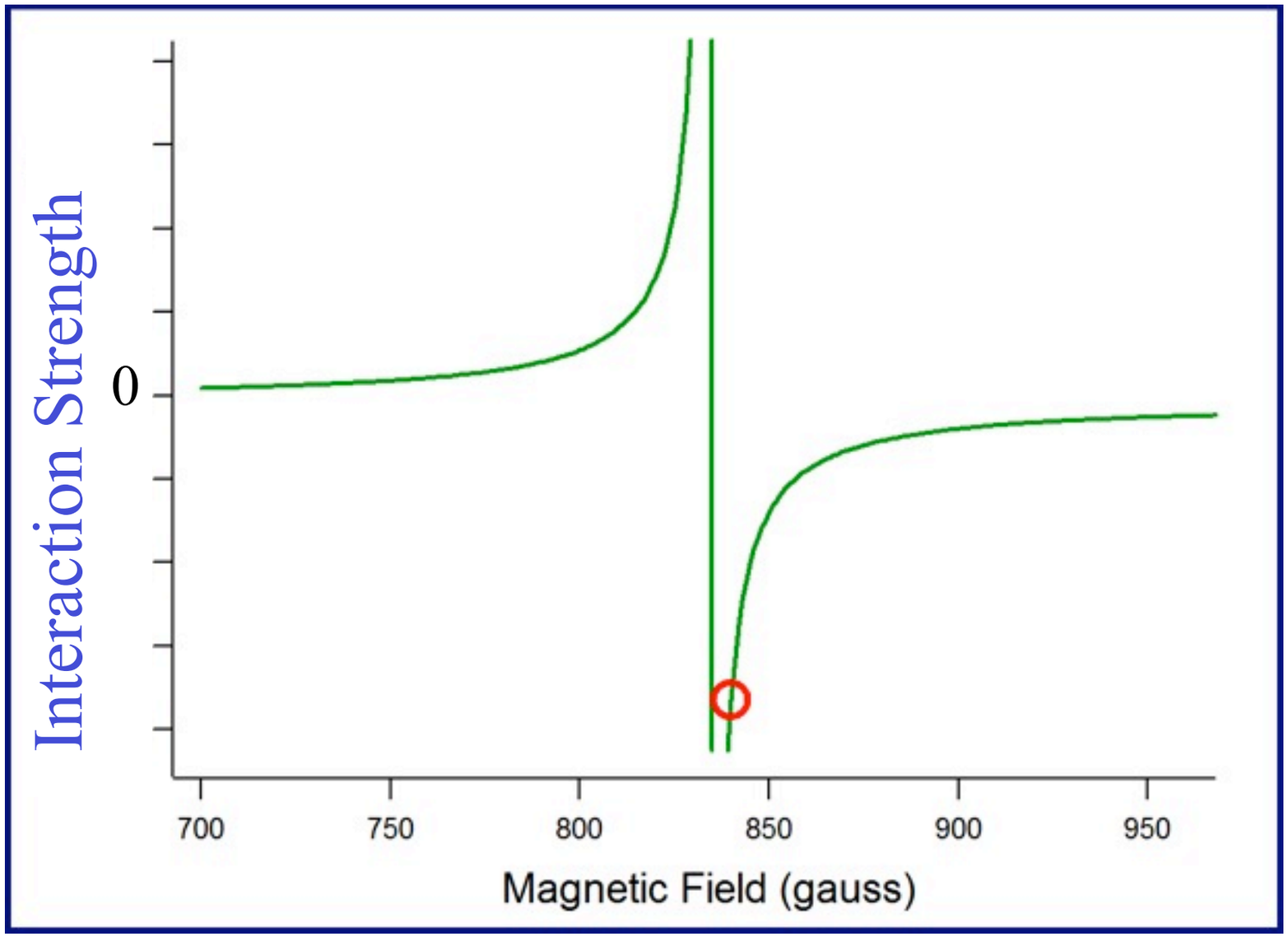

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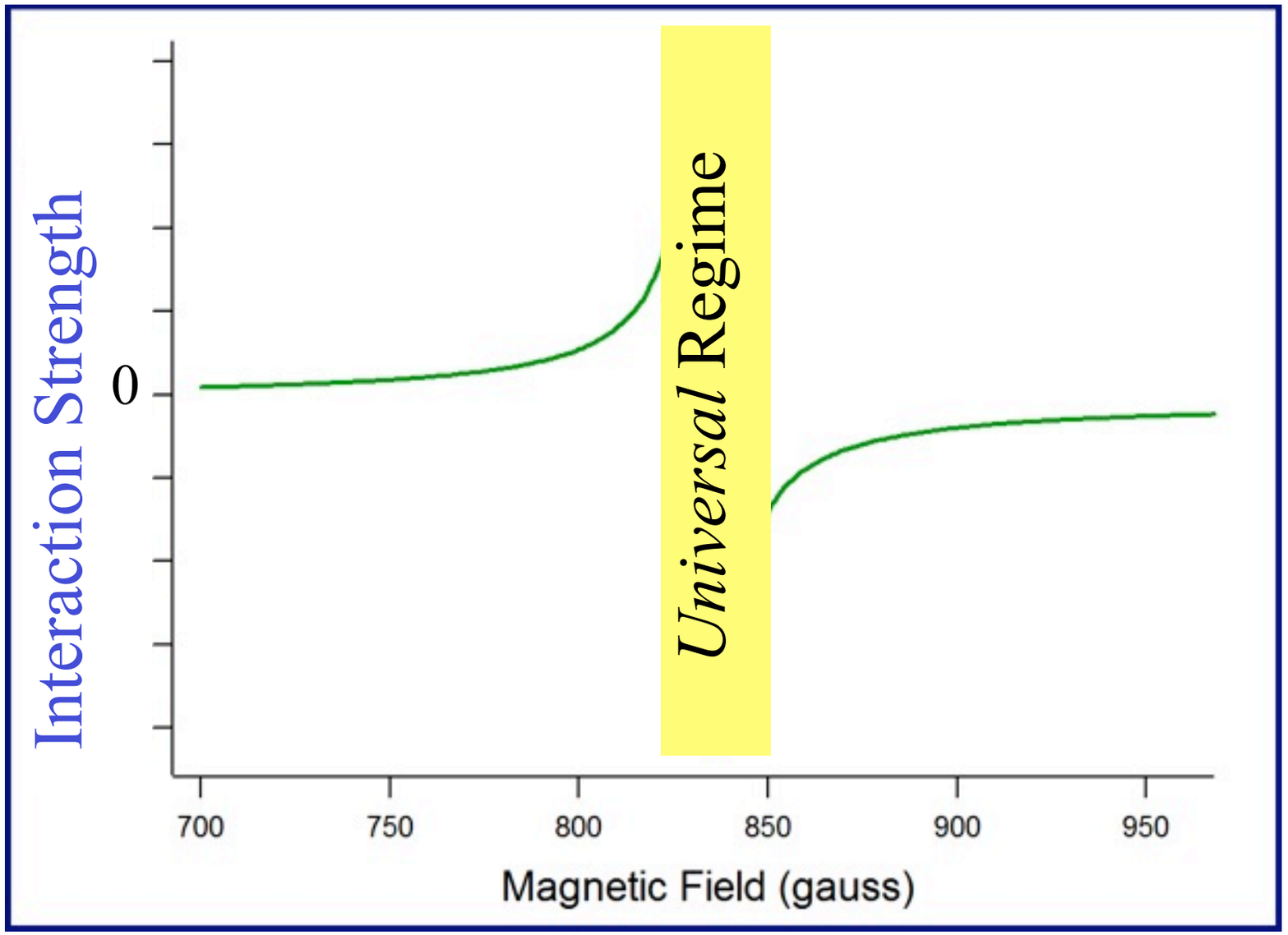
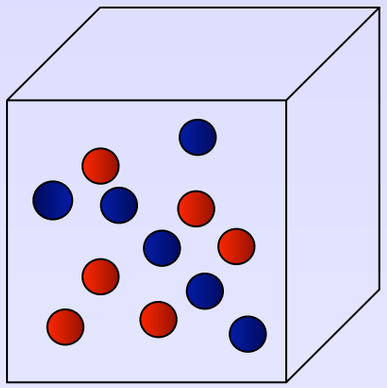


The *Universal* Regime: *Natural Units and Rulers*



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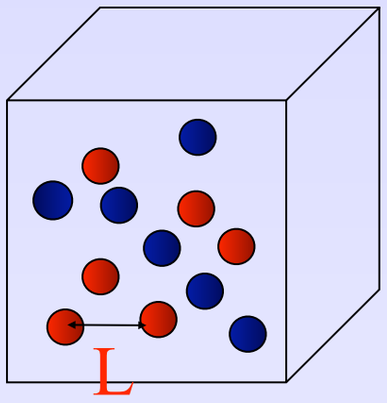

Interparticle spacing L
becomes the *only* length scale.

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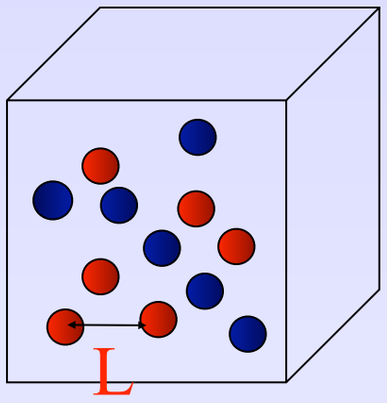

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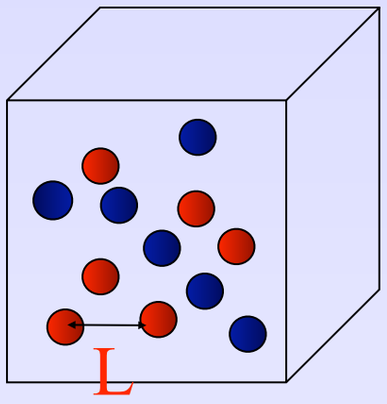

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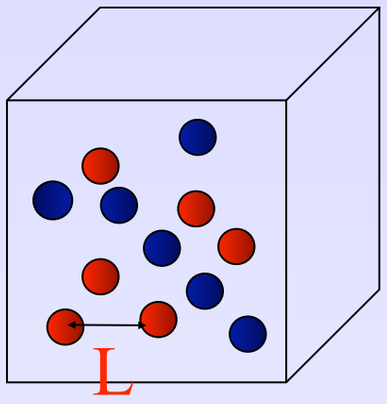

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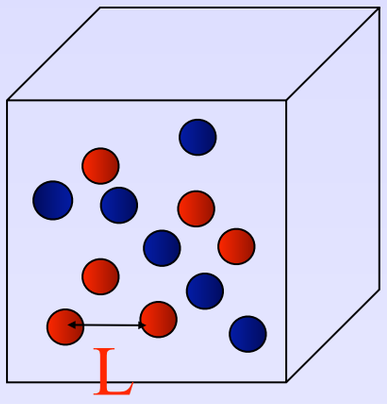

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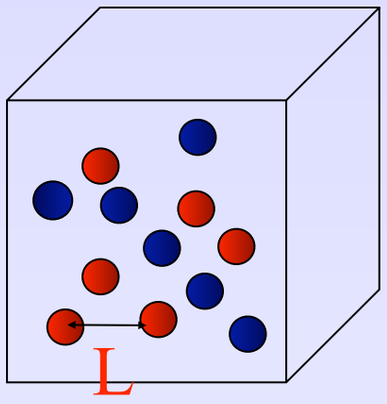

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Quantum Viscosity Unit

Strongly Interacting Systems in Nature

Duke Physics

Atom Cooling and Trapping

Strongly Interacting Systems in Nature

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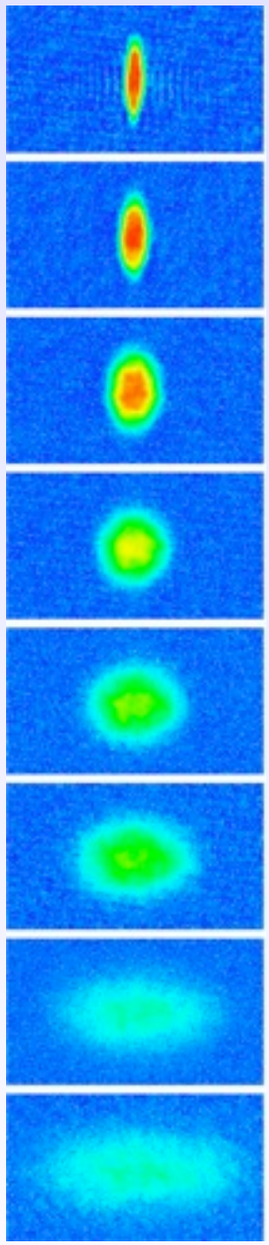
Atom Cooling and Trapping



Strongly Interacting ^{6}Li gas
$T = 10^{-7}$ K

Duke, Science (2002)

Strongly Interacting Systems in Nature

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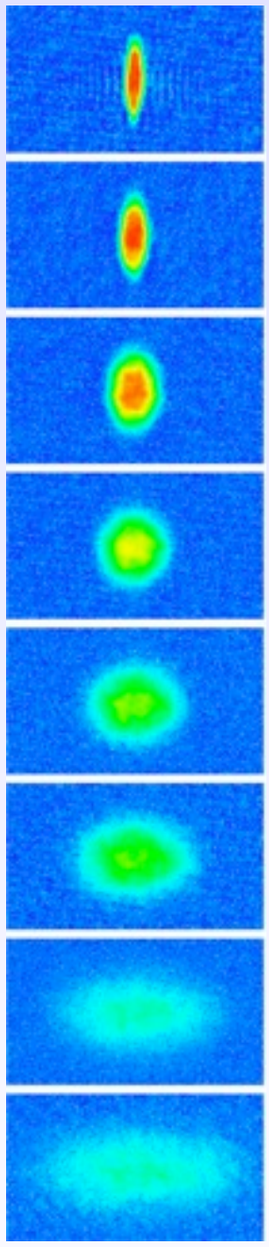

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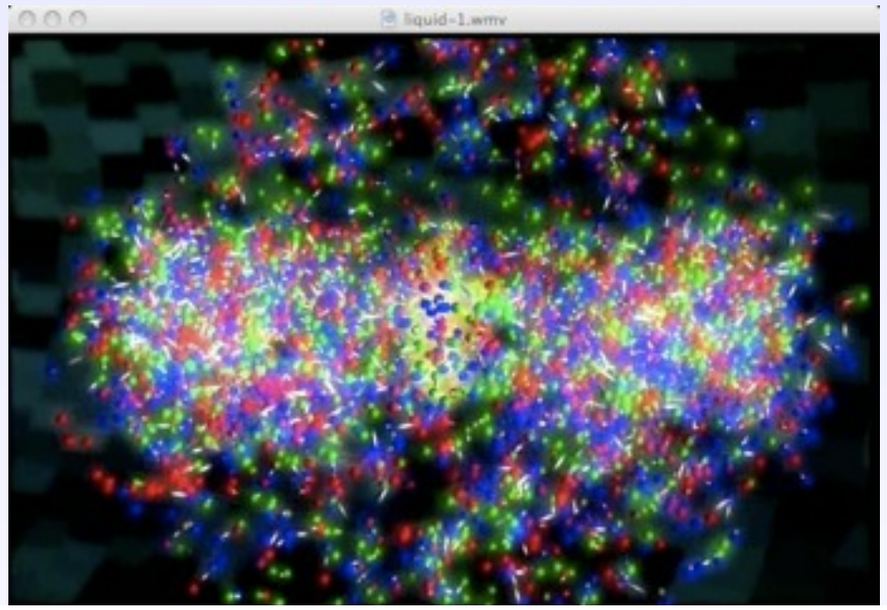

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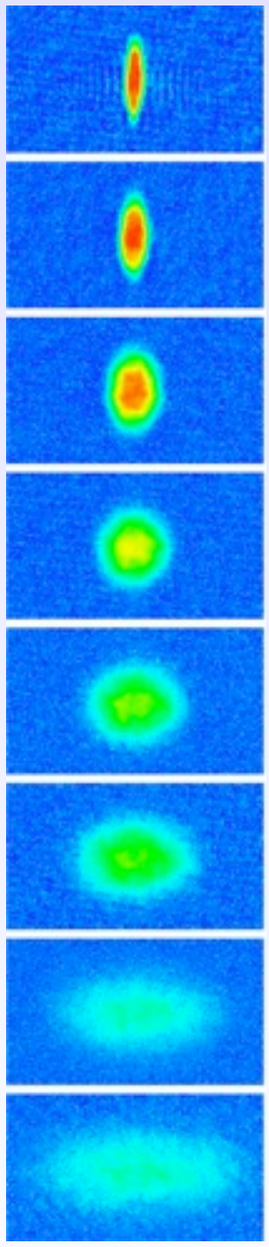

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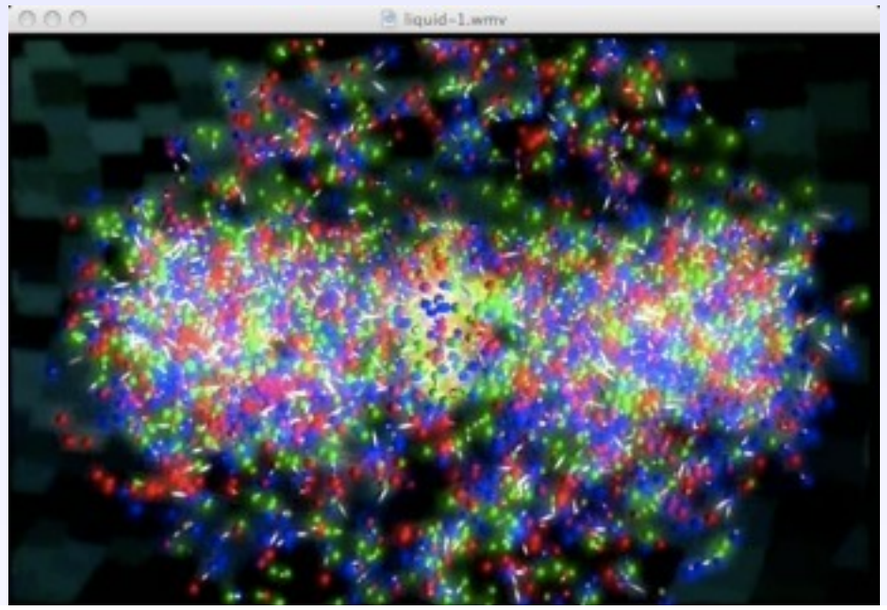


Quark-gluon plasma $T = 10^{12}$ K

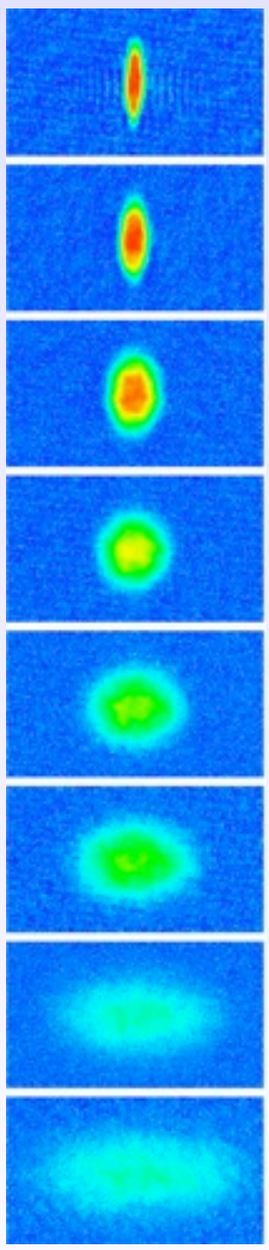
→ Similar "Elliptic" Flow ←

Strongly Interacting Systems in Nature

Duke Physics

Atom Cooling and Trapping

- Ultracold Atomic ^{6}Li Gas
- Quark-Gluon Plasma
- High T_c Superconductors
- Neutron Matter
- Black Holes in String Theory



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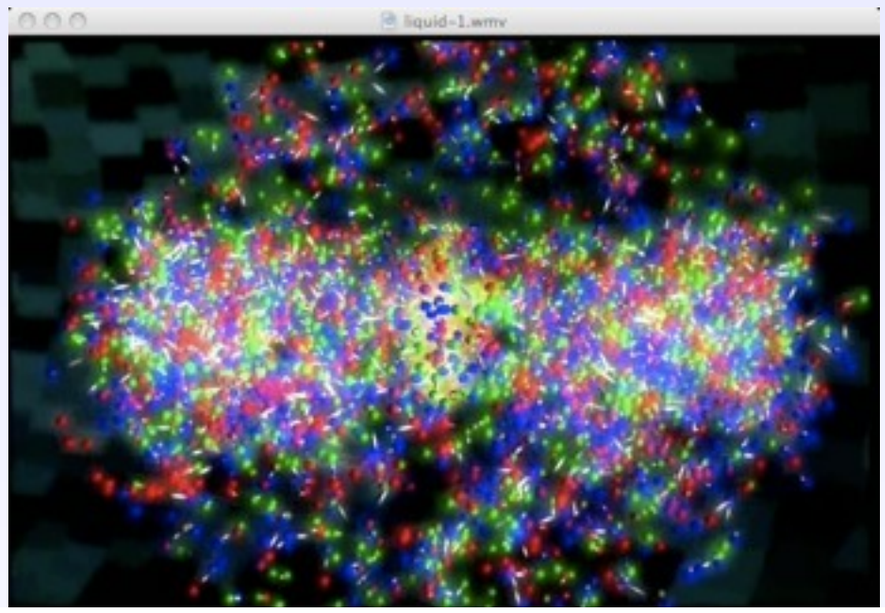

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The Minimum Viscosity Conjecture—String Theory

Duke Physics

Atom Cooling and Trapping

The Minimum Viscosity Conjecture—String Theory

Duke Physics
Atom Cooling and Trapping

$$\frac{\text{viscosity}}{\text{entropy}} = \frac{\eta}{s} \geq \frac{1}{4\pi}$$

Kovtun et al., PRL 2005

The Minimum Viscosity Conjecture—String Theory

Duke Physics

Atom Cooling and Trapping

Resistance to flow—hydrodynamic properties

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Disorder—thermodynamic properties

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Atom Cooling and Trapping

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Disorder—thermodynamic properties

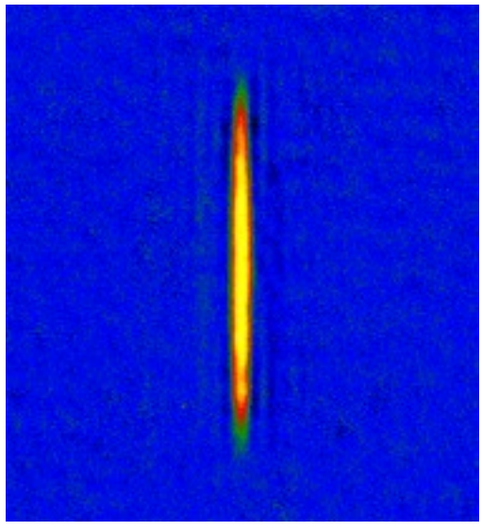
Is a Strongly-interacting atomic ^{6}Li gas a fluid with the minimum viscosity?

Measuring the Energy E and Entropy S

Duke Physics

Atom Cooling and Trapping

Measuring the Energy E and Entropy S



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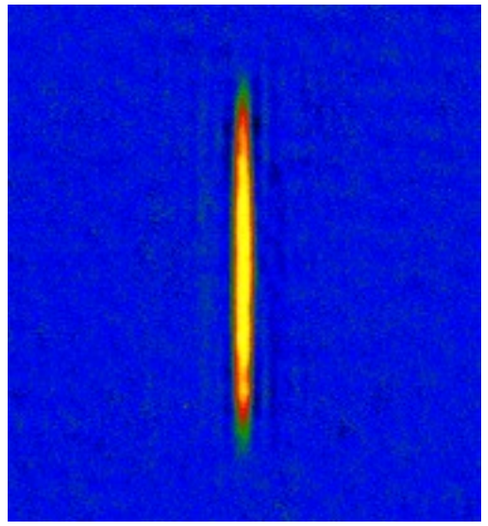
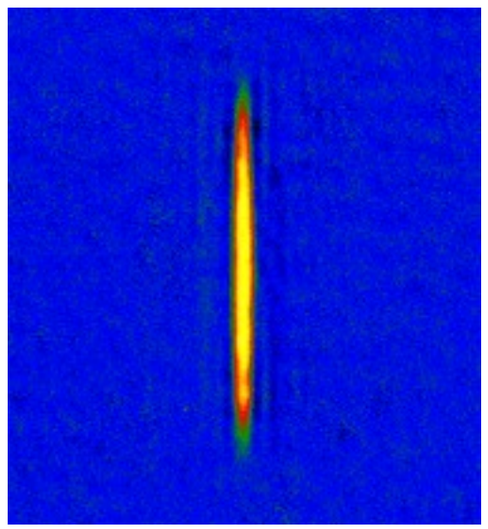


For a *universal* quantum gas,
the energy E is determined
by the *cloud size*

Duke, PRL (2005)

Measuring the Energy E and Entropy S

Duke Physics
Atom Cooling and Trapping



For a *universal* quantum gas,
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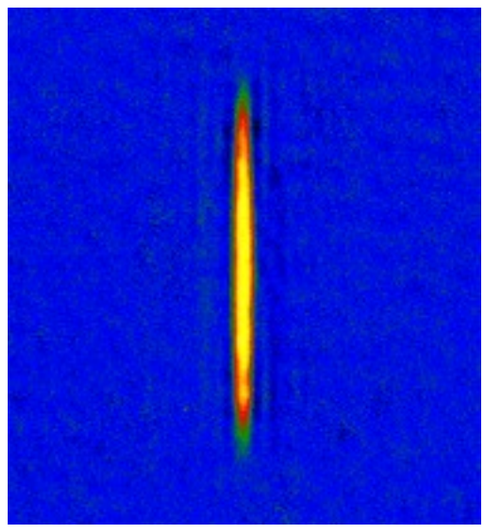
Duke, PRL (2005)

For a *weakly interacting* quantum gas
the entropy S can always be determined
from the *cloud size* (textbook problem)

Measuring the Energy E and Entropy S

Duke Physics

Atom Cooling and Trapping



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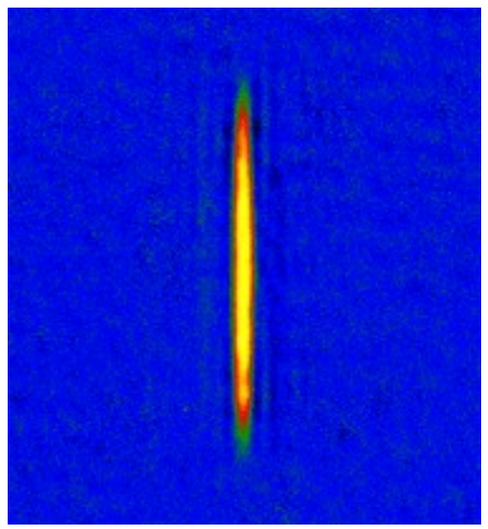
Experiment

Measuring the Energy E and Entropy S

Duke Physics

Atom Cooling and Trapping



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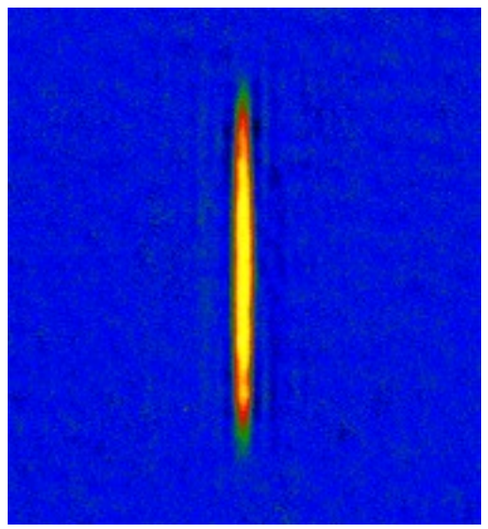
Experiment

Start
Universal strongly
Interacting

Measuring the Energy E and Entropy S

Duke Physics
Atom Cooling and Trapping

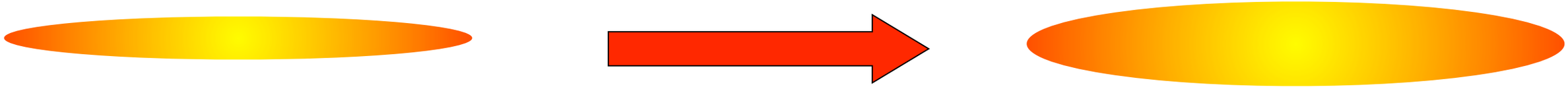


For a *universal* quantum gas,
the energy E is determined
by the *cloud size*

Duke, PRL (2005)

For a *weakly interacting* quantum gas
the entropy S can always be determined
from the *cloud size* (textbook problem)

Experiment



Start
Universal strongly Interacting

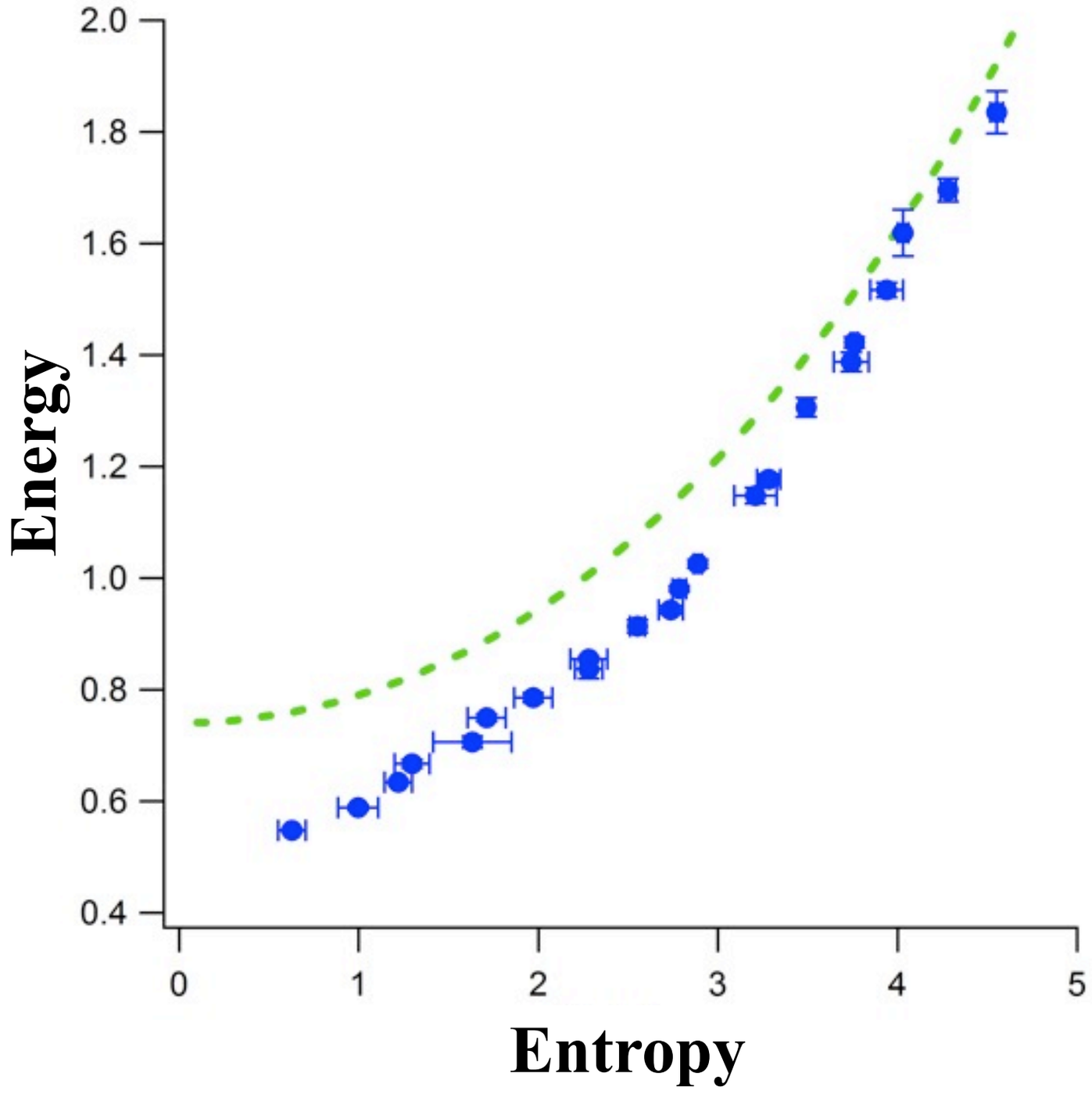
Sweep magnetic field

Duke, PRL (2007)

End
Weakly interacting

Energy versus Entropy

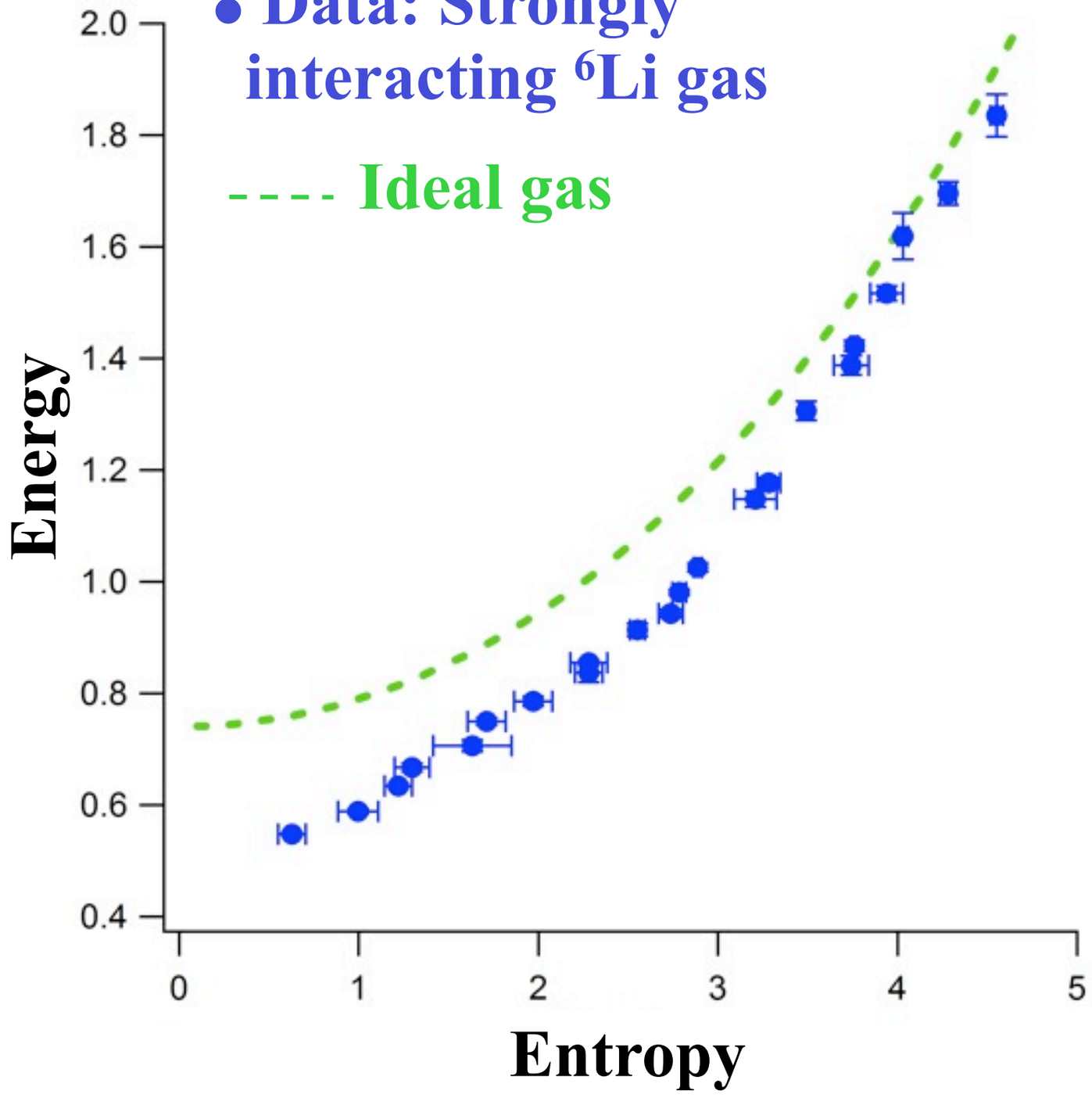
Energy versus Entropy



Energy versus Entropy

- **Data: Strongly interacting ^{6}Li gas**

---- Ideal gas



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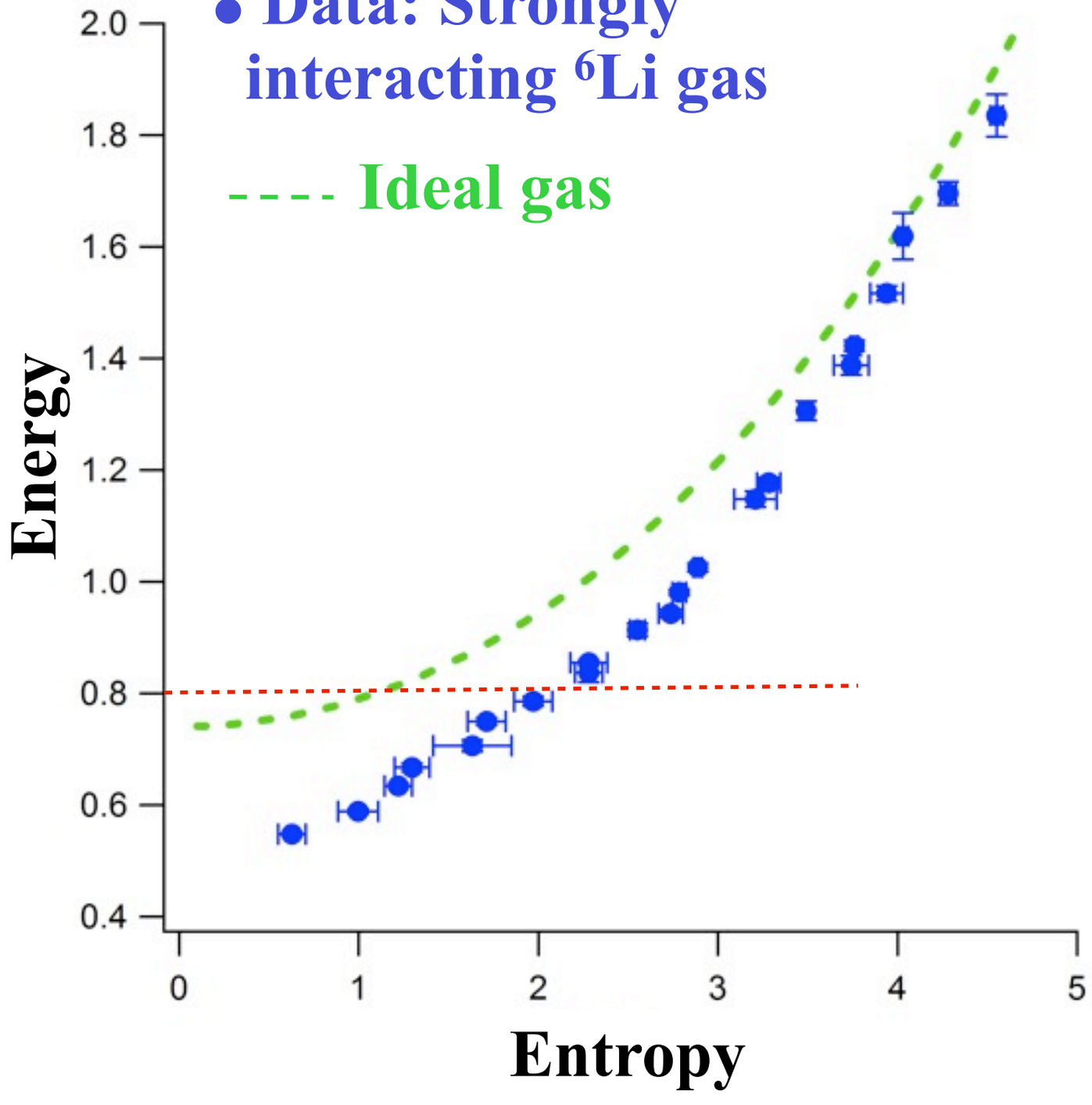

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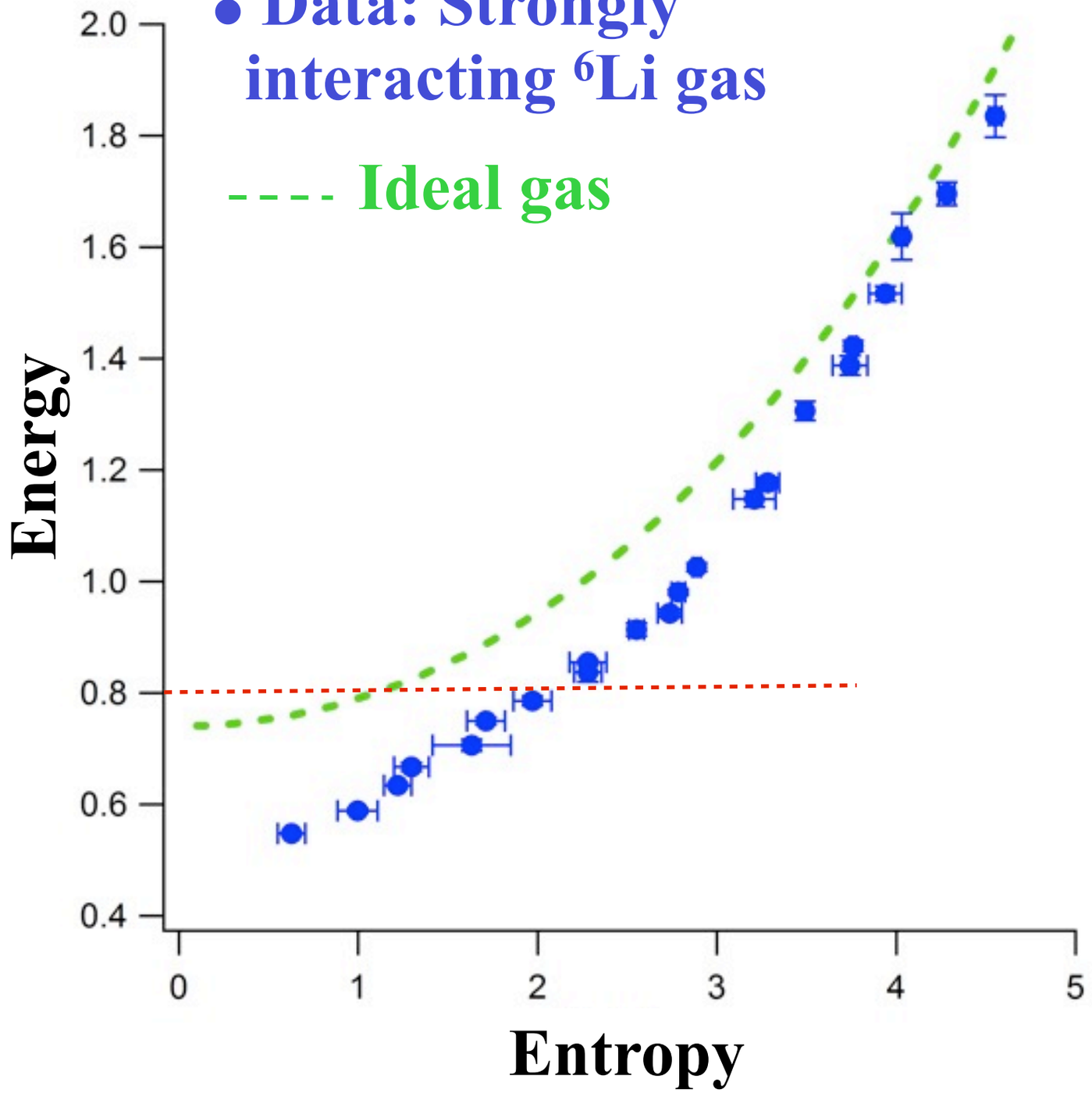

Critical temperature for the *superfluid transition* = 0.20 (natural units)

Energy versus Entropy

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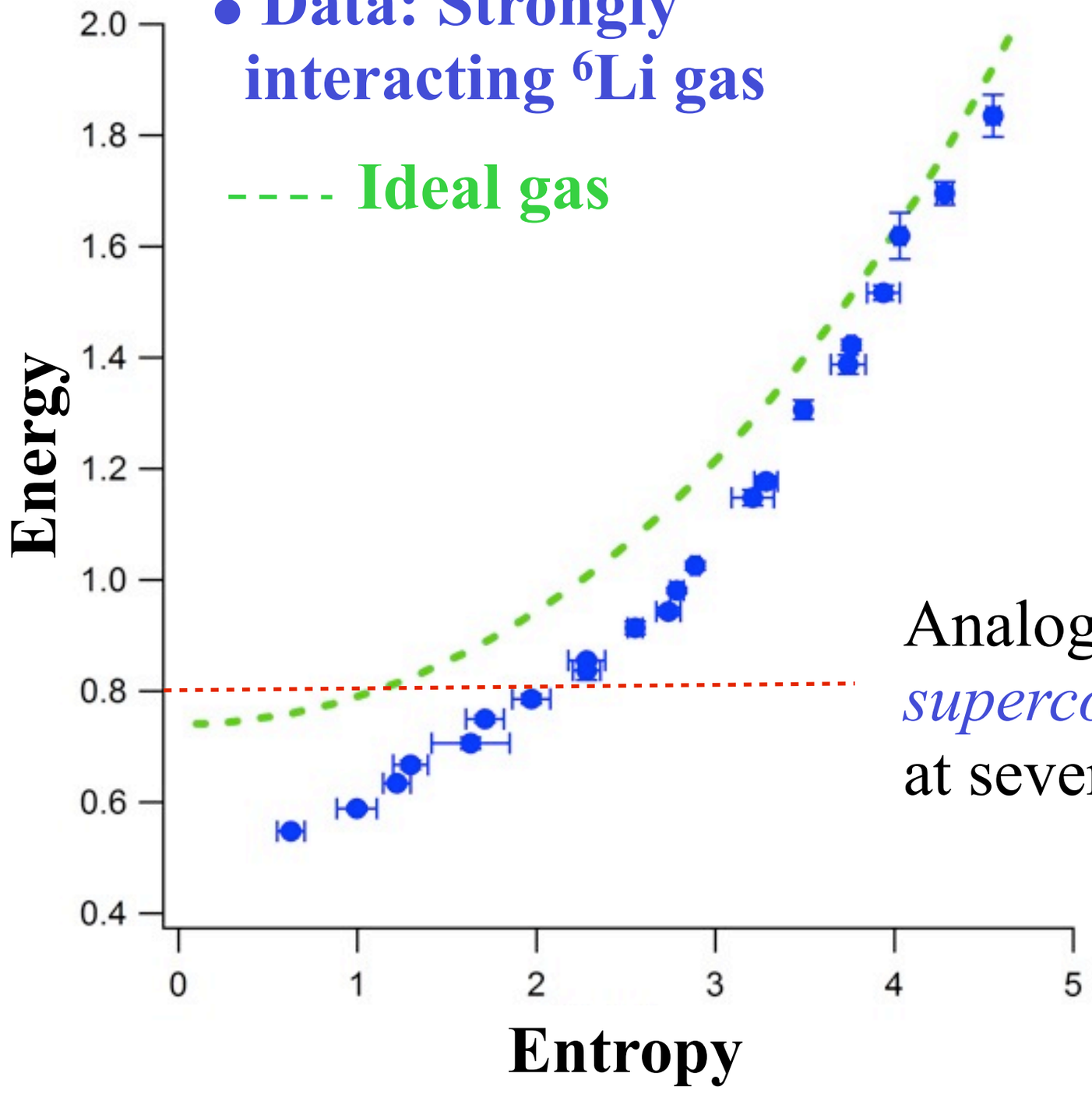


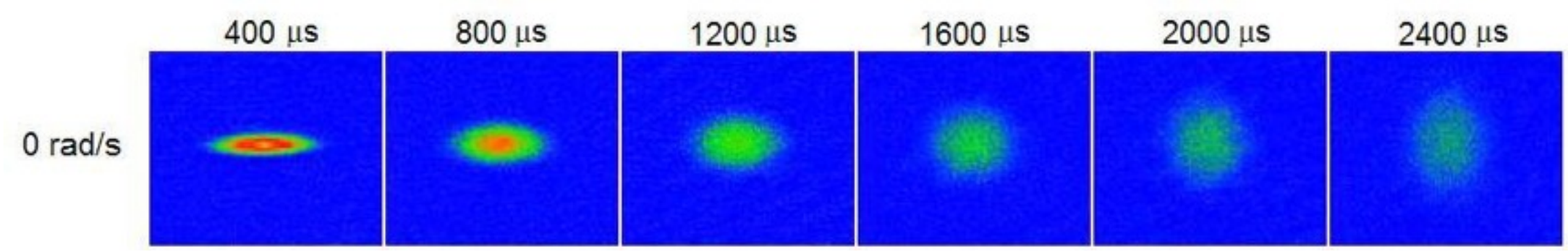
Critical temperature for the *superfluid transition* = 0.20 (natural units)

Analog of a *super-high temperature superconductor* that would work at several *thousand* degrees!

Measuring Viscosity from the expansion of a rotating gas

Duke Physics

Atom Cooling and Trapping



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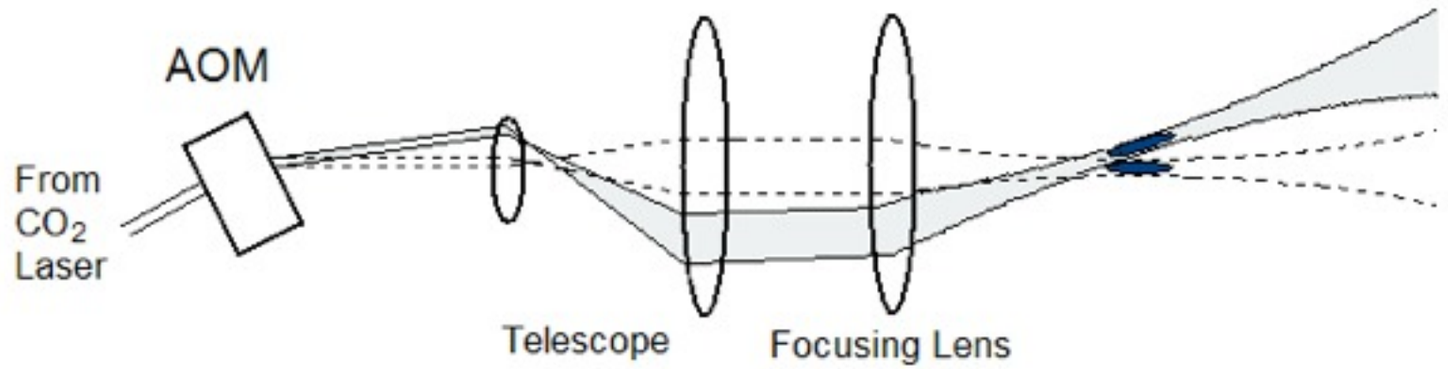
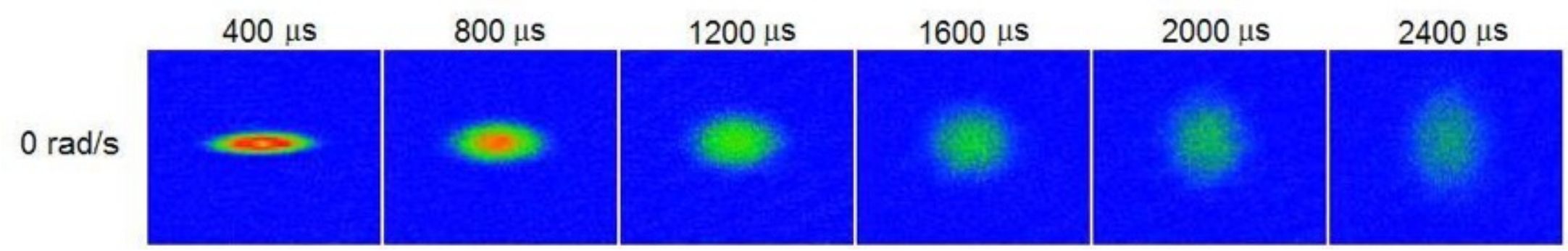
Atom Cooling and Trapping





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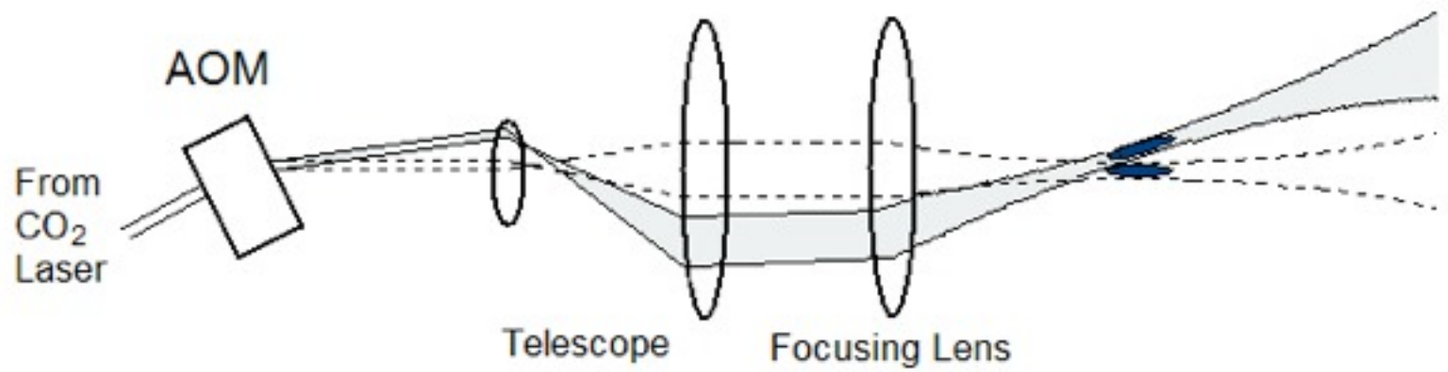
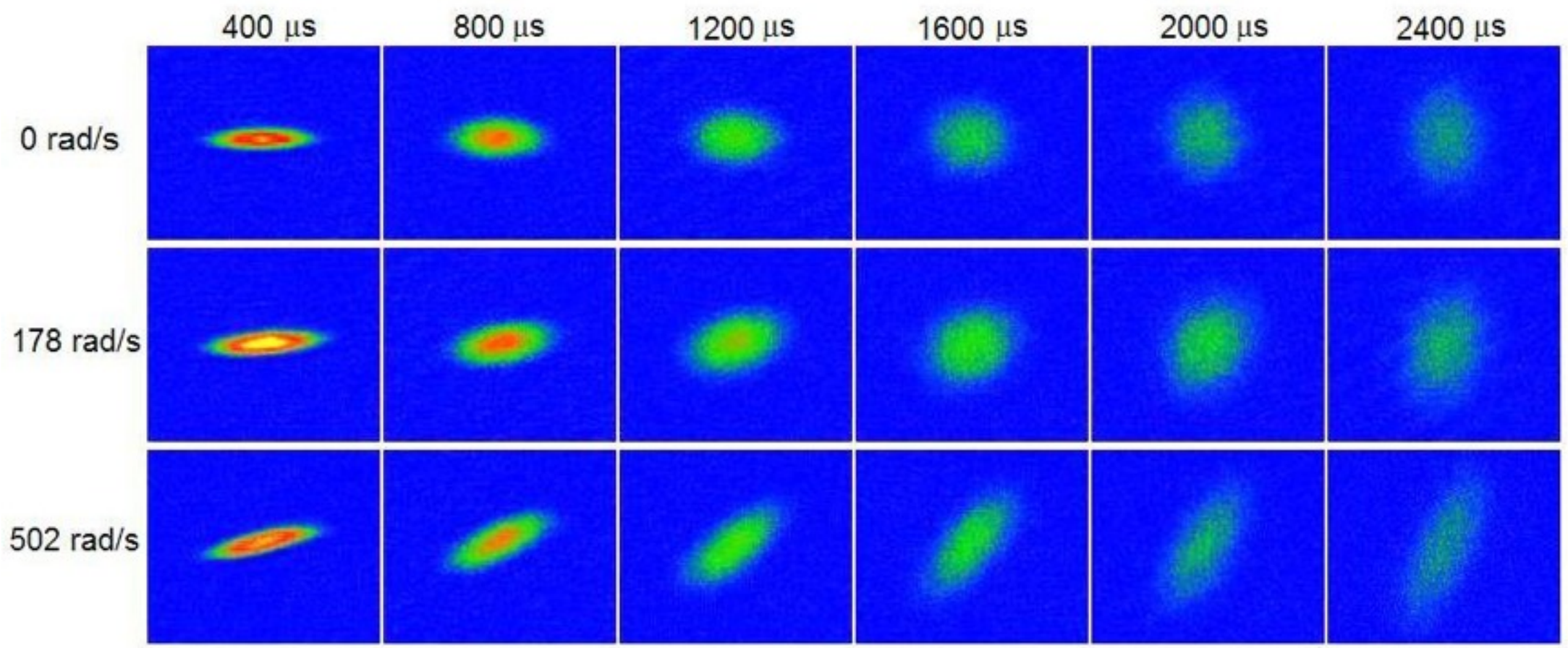
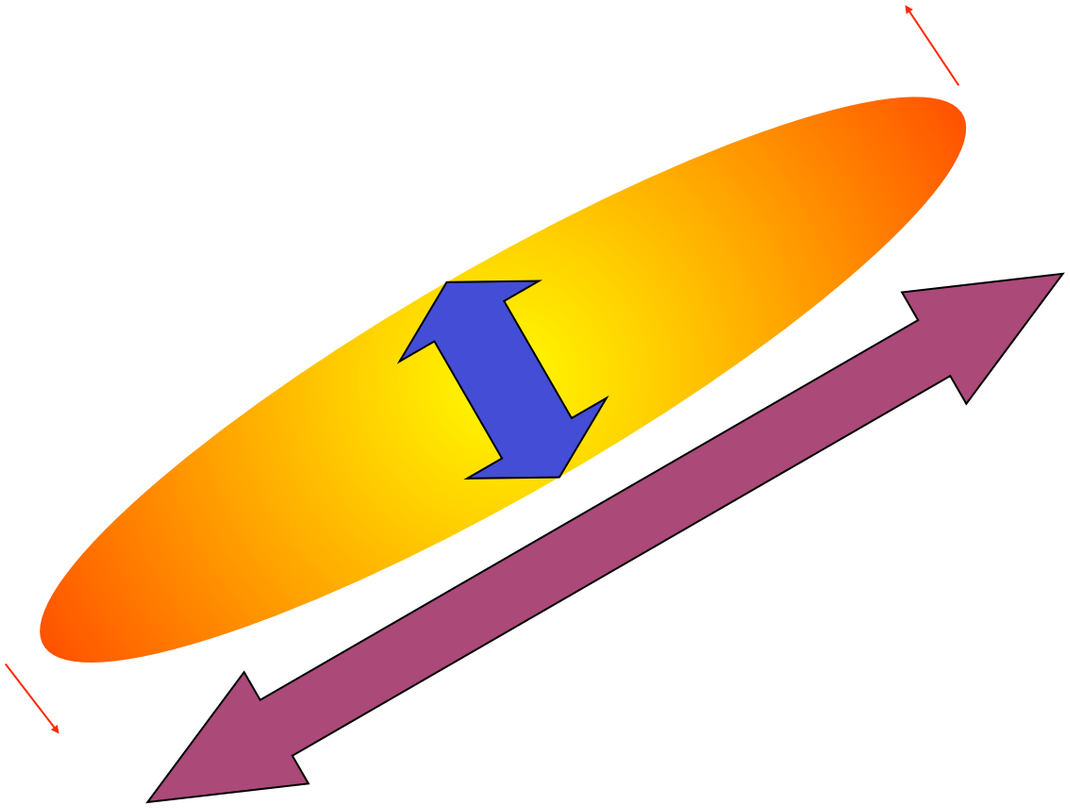




Measure the angle of the cloud

Duke Physics

Atom Cooling and Trapping



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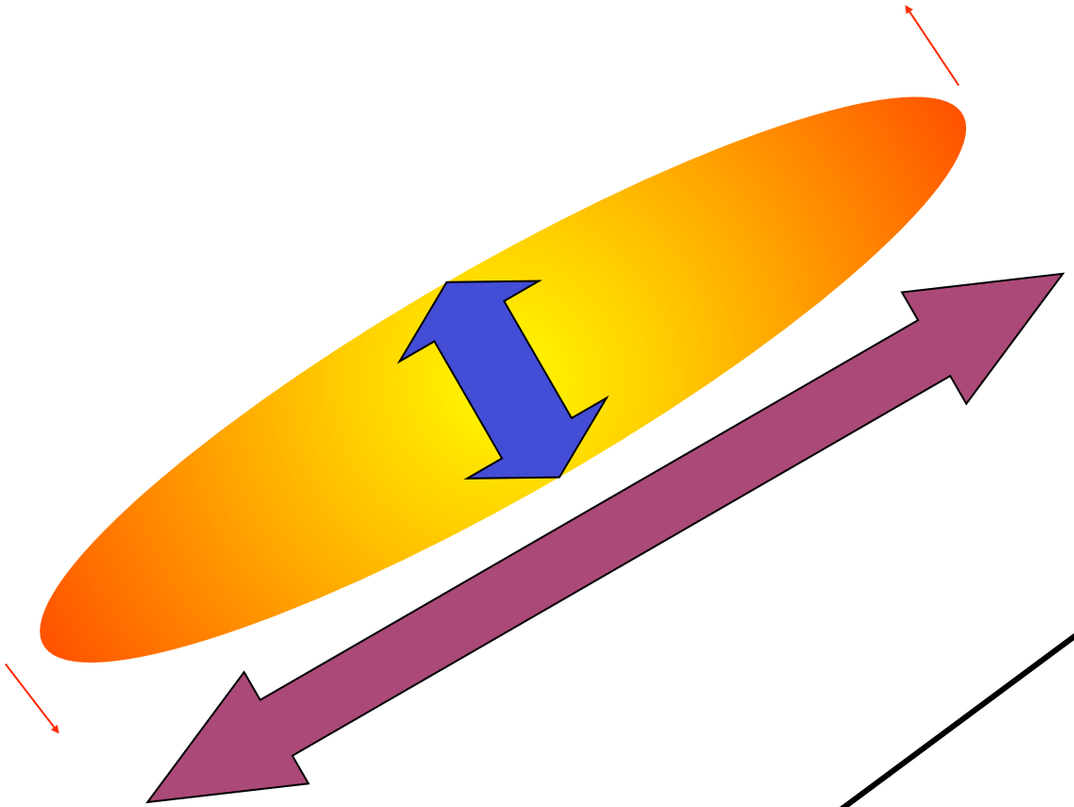
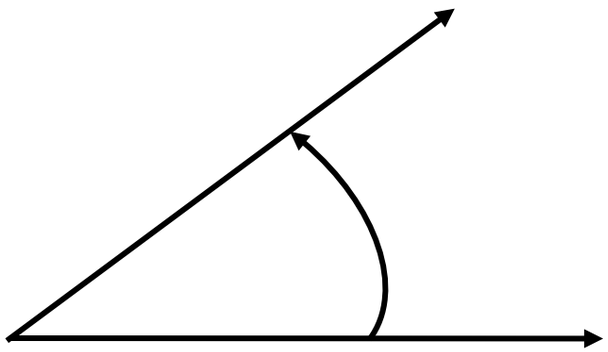


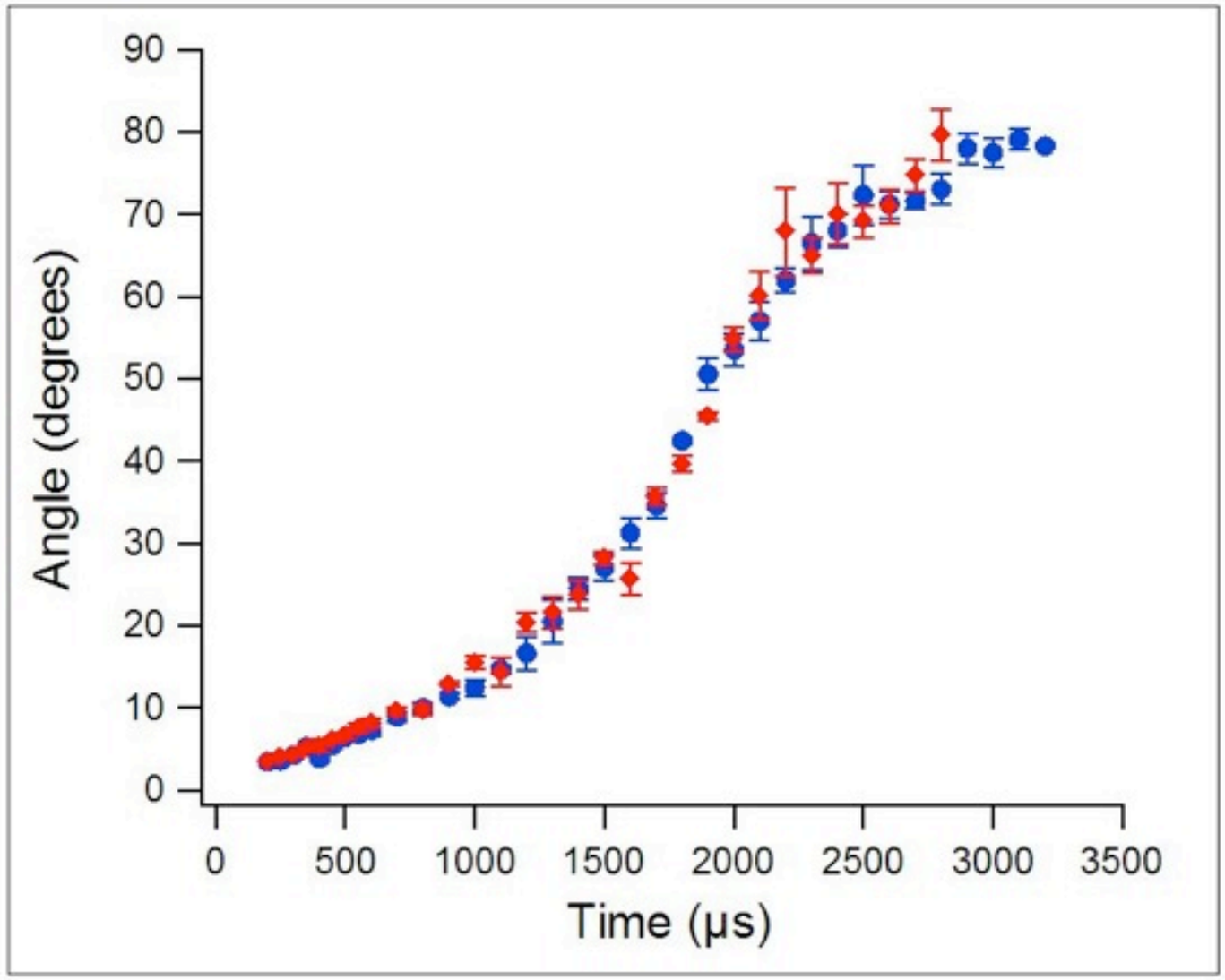


Measure the *angle* of the *long* axis of the rotating cloud with respect to the laboratory axis

How low is the viscosity?

Duke Physics

Atom Cooling and Trapping



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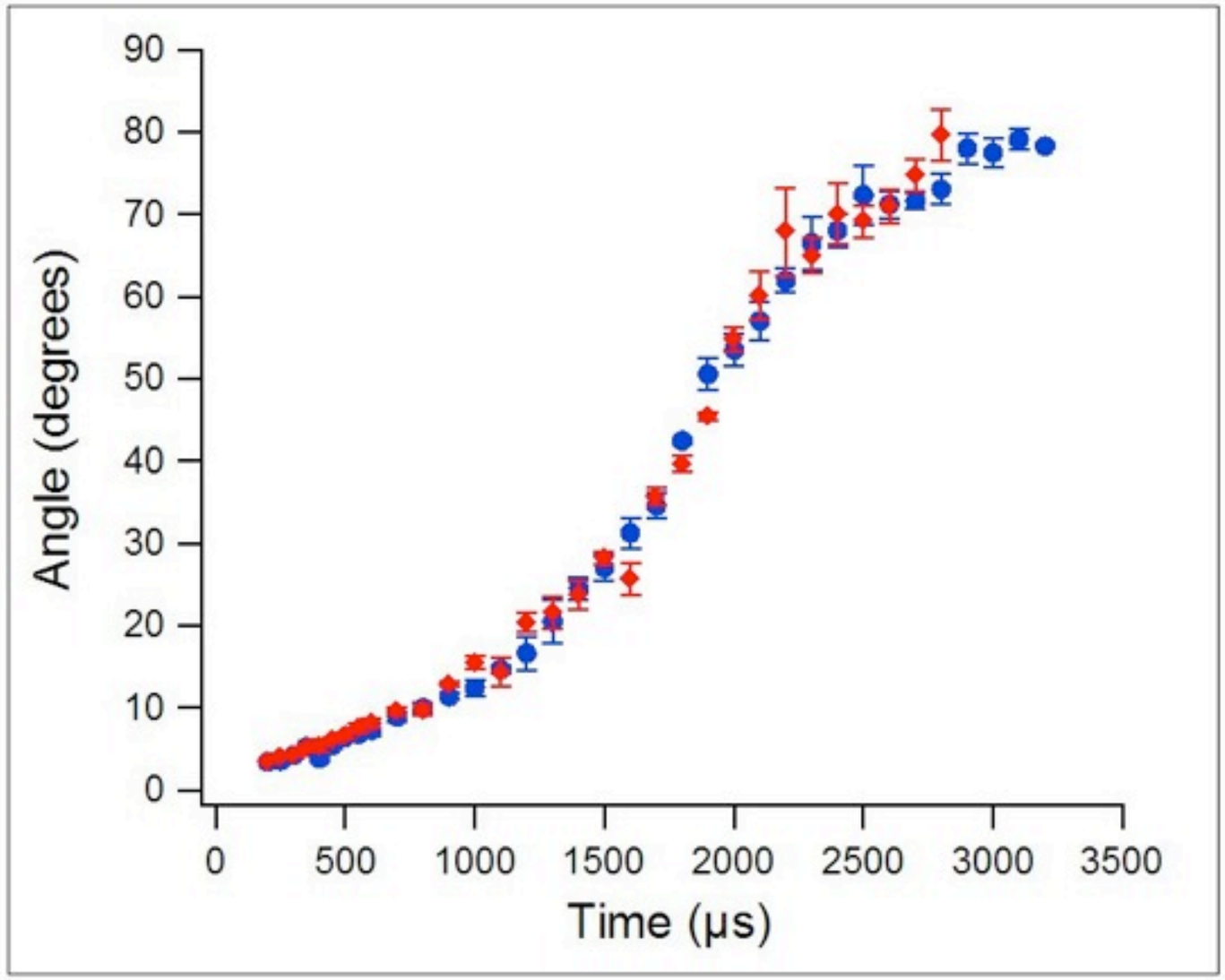

Rotates *faster* as it *expands*—*opposite* to the behavior of an ice-skater!

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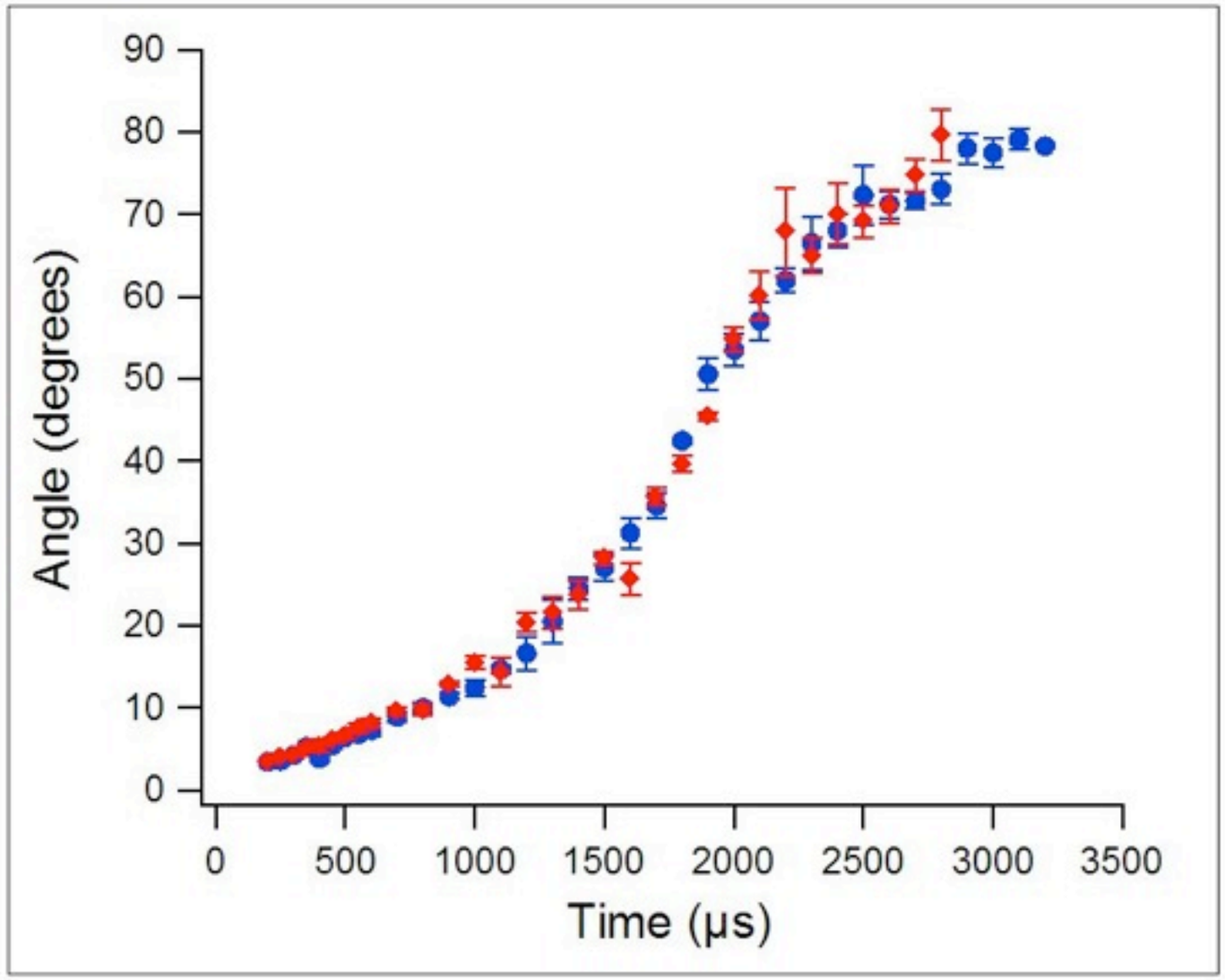

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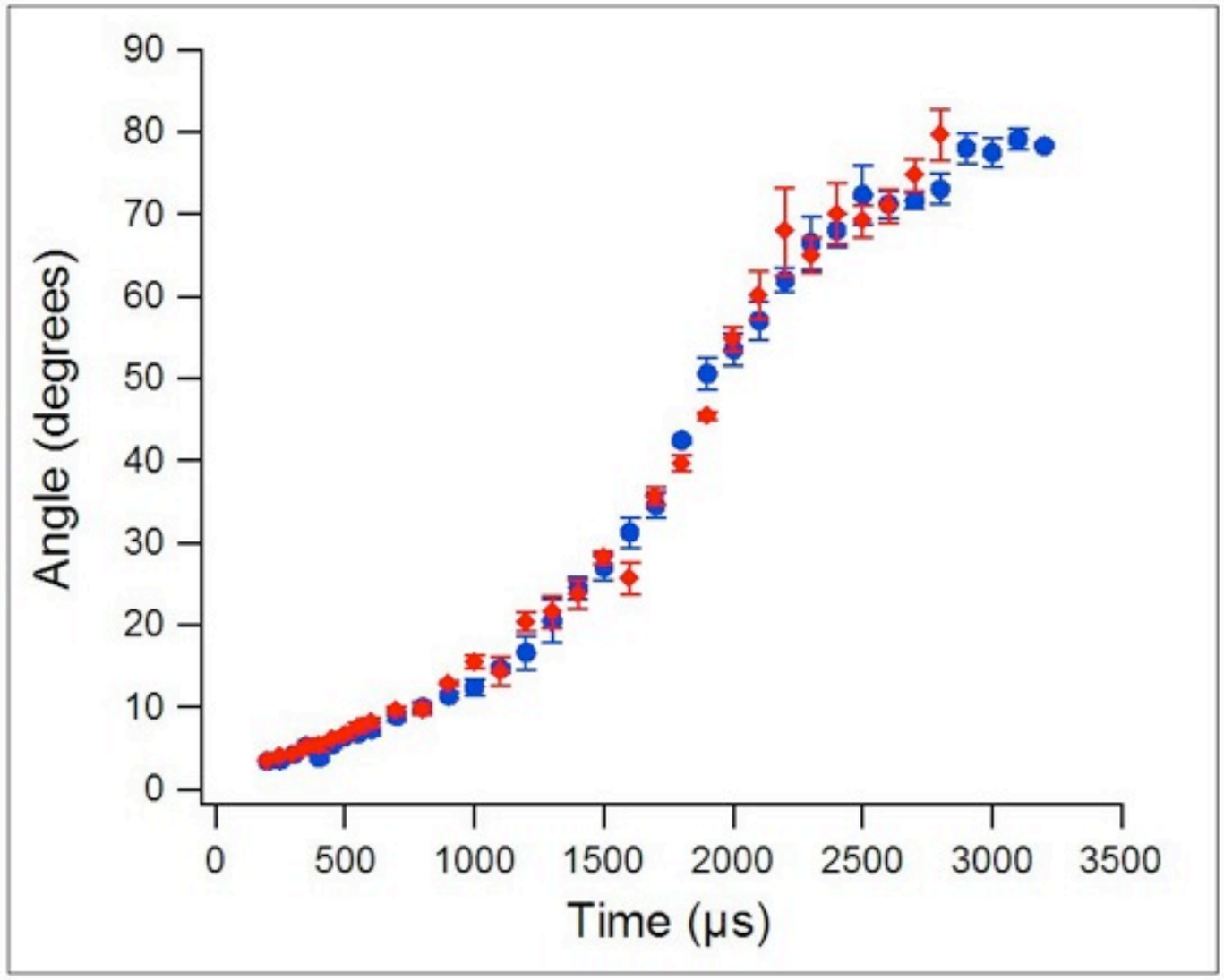
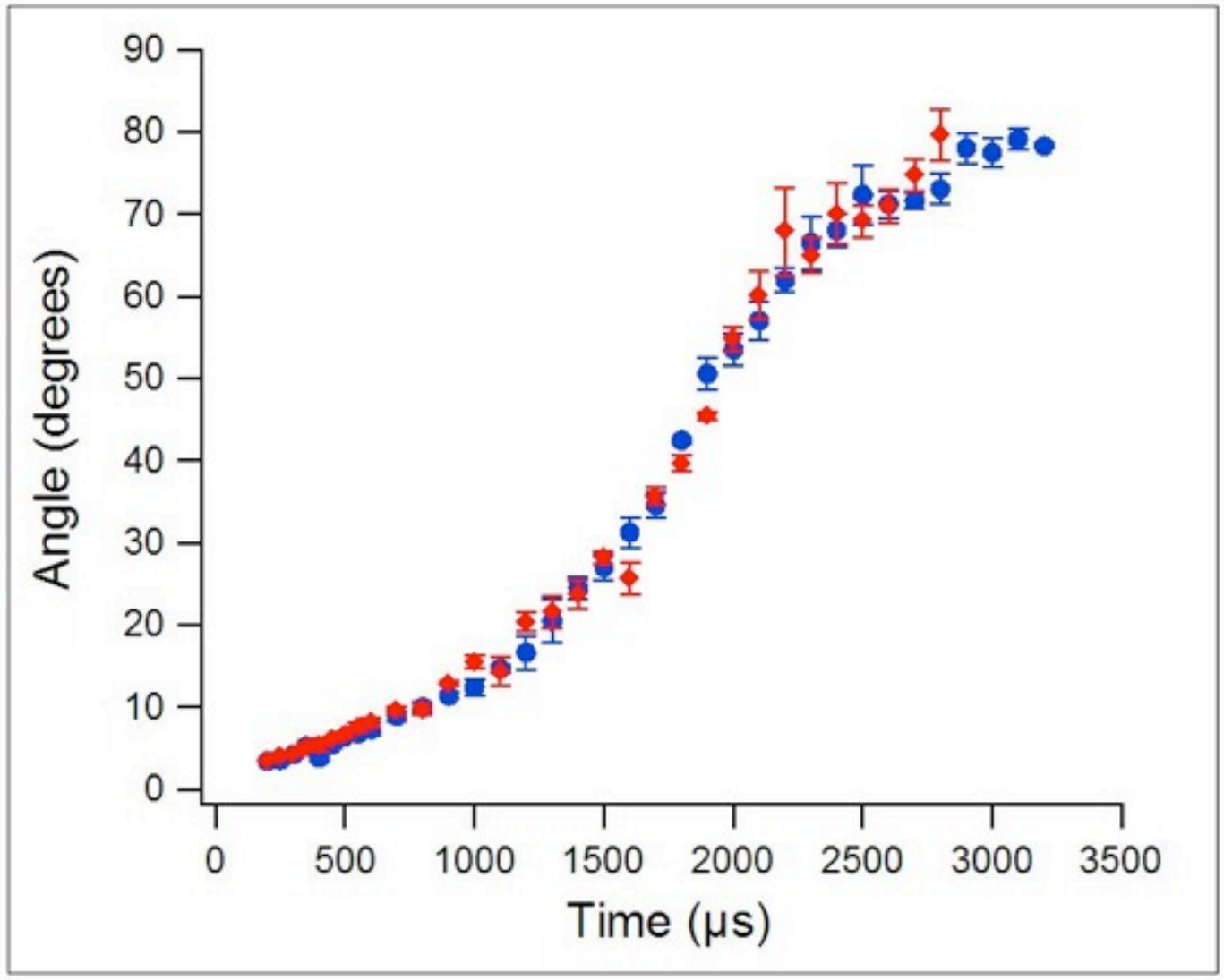


- Superfluid, $\Omega_0 = 178$ rad/s

How low is the viscosity?



- Superfluid, $\Omega_0 = 178$ rad/s
- Normal Fluid, $\Omega_0 = 178$ rad/s

How low is the viscosity?

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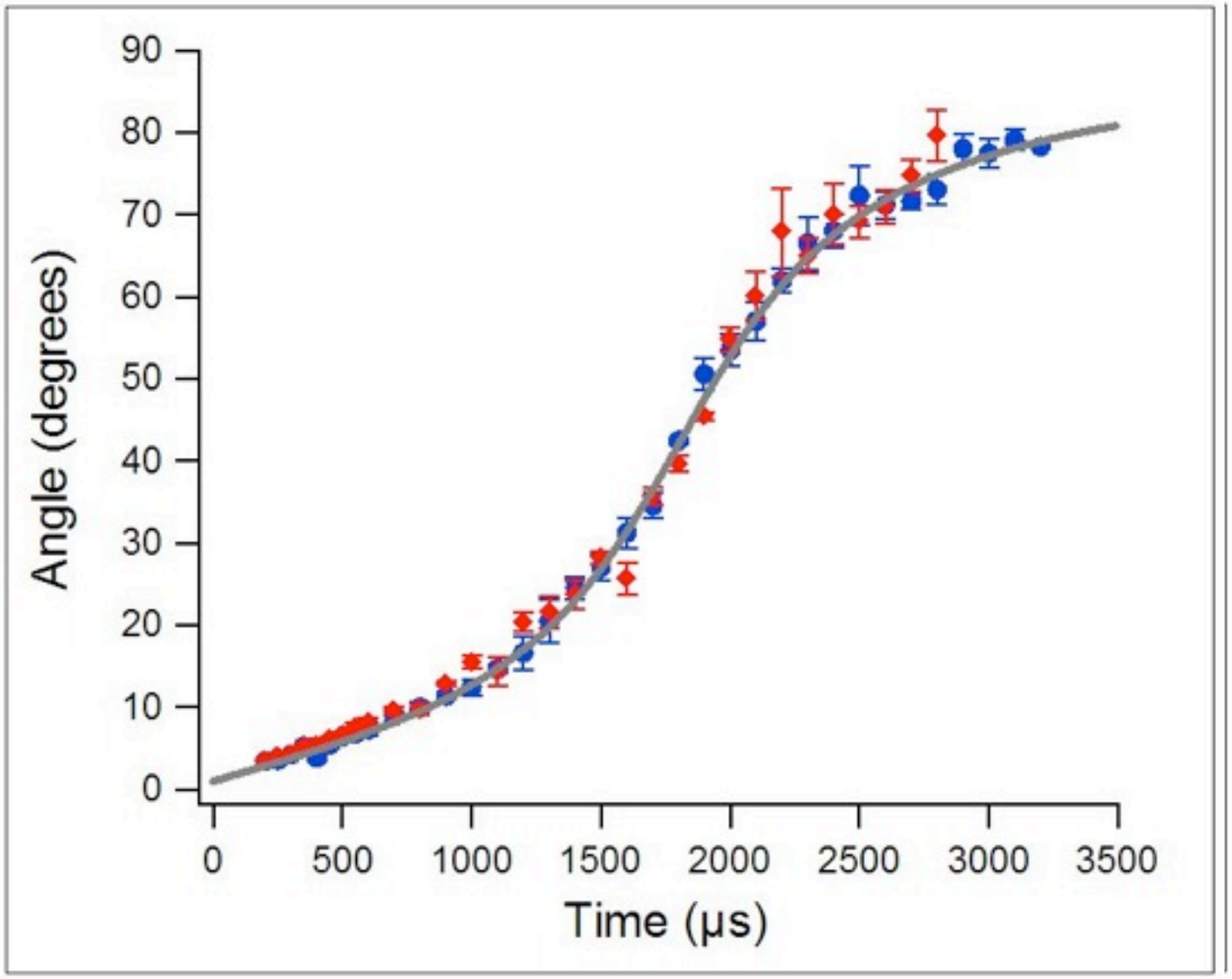
Atom Cooling and Trapping



Theory—superfluid flow

- Superfluid, $\Omega_0 = 178$ rad/s
- Normal Fluid, $\Omega_0 = 178$ rad/s

How low is the viscosity?

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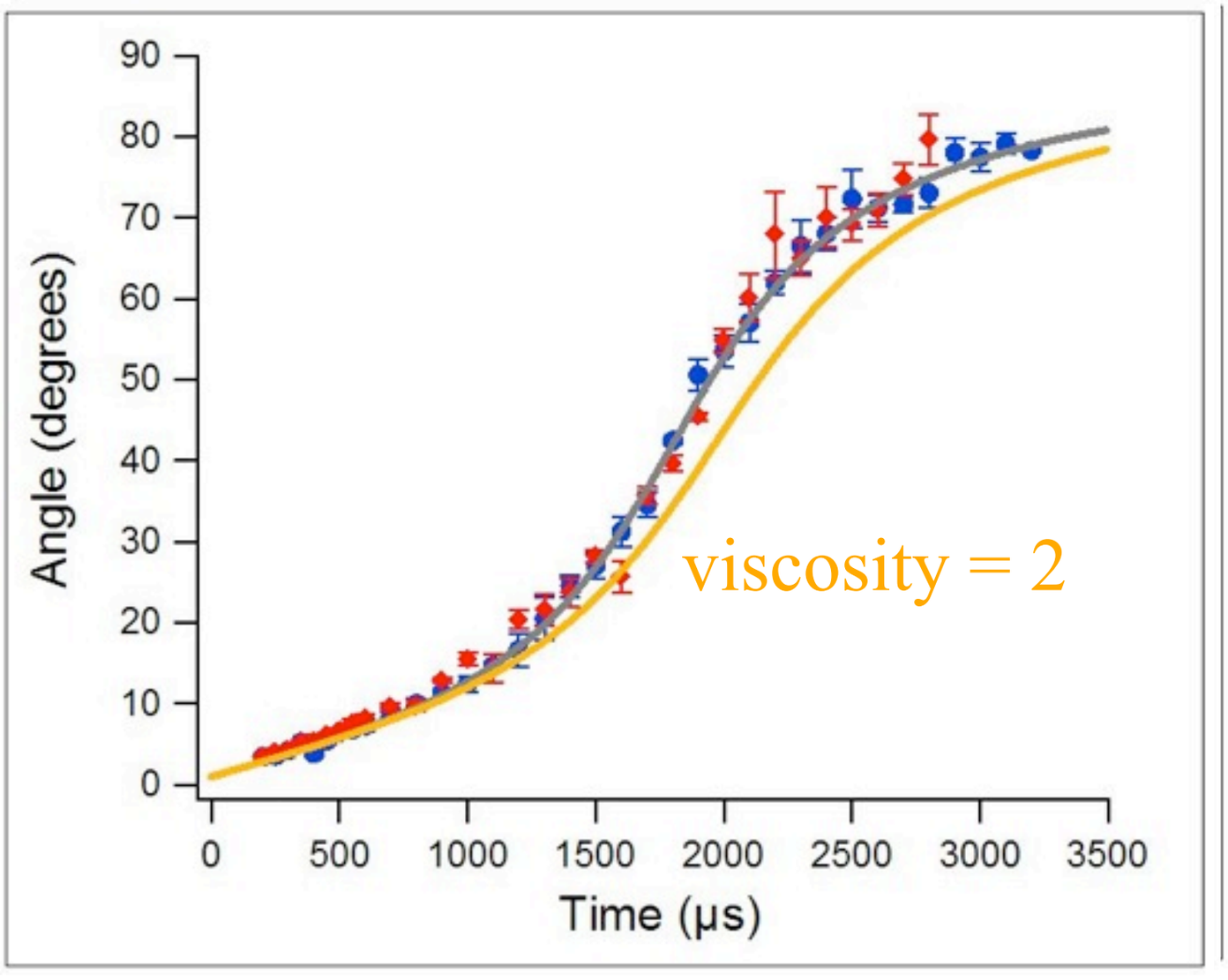
Atom Cooling and Trapping



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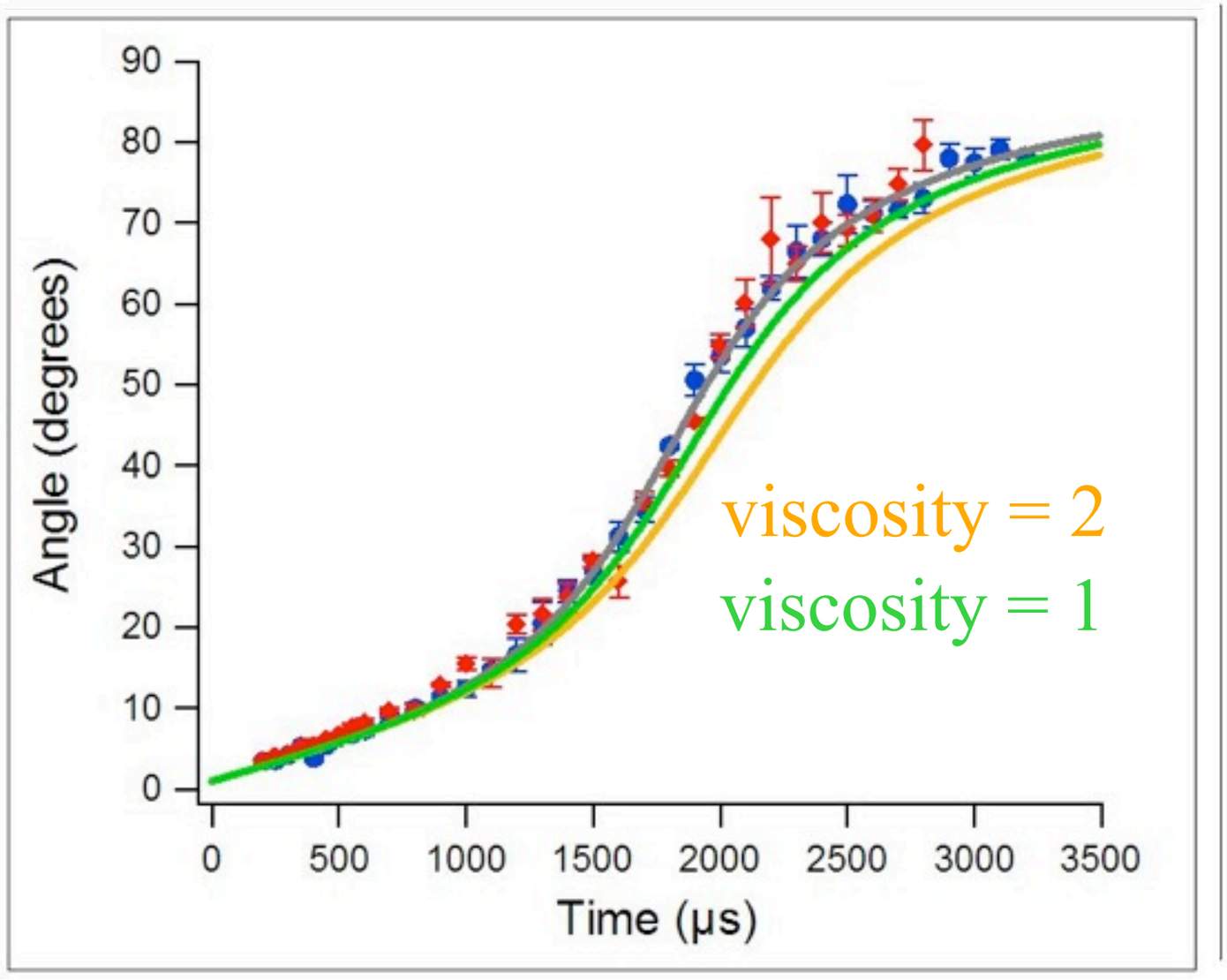

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Viscosity/Entropy (natural units)

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Atom Cooling and Trapping

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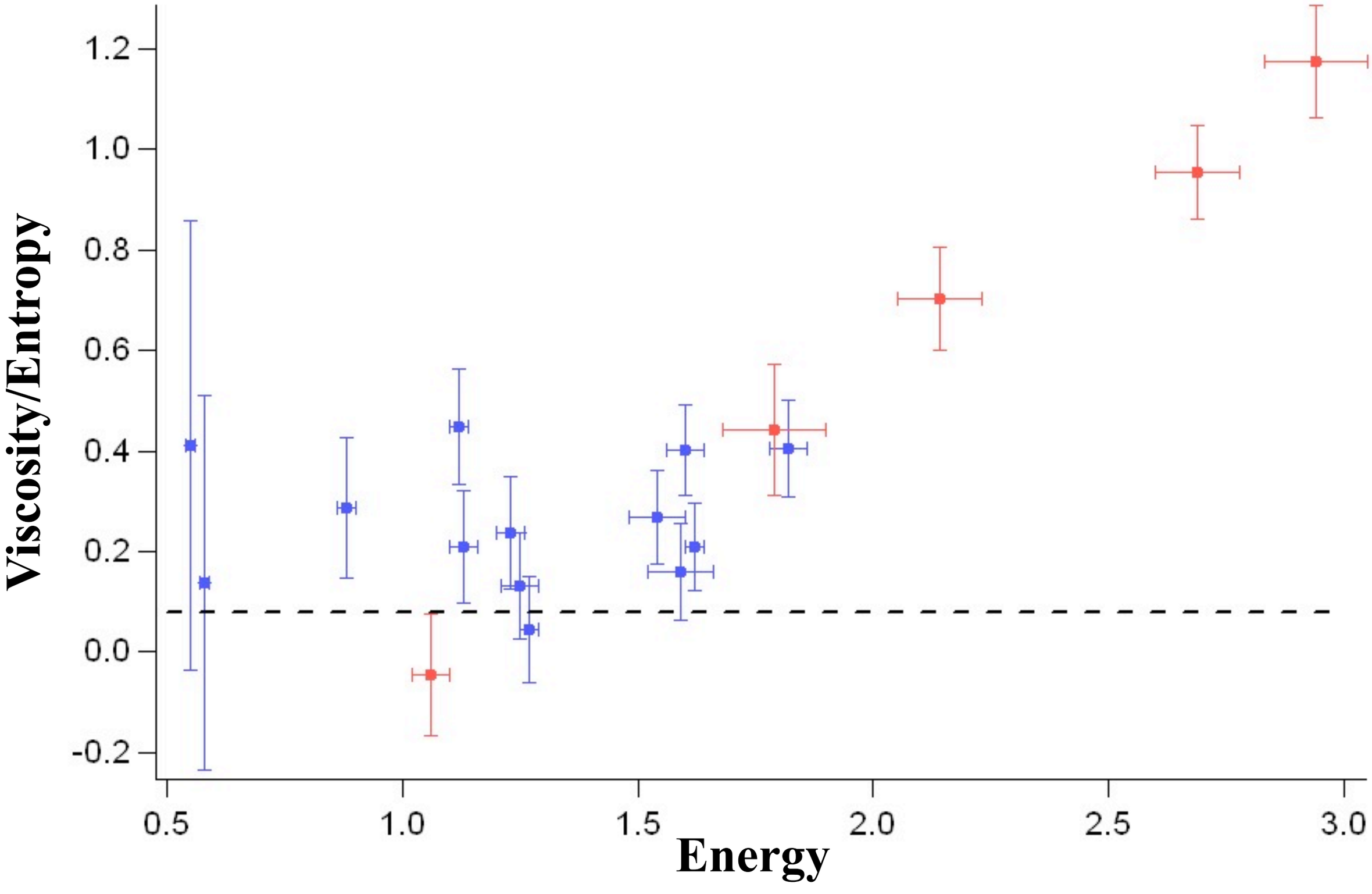

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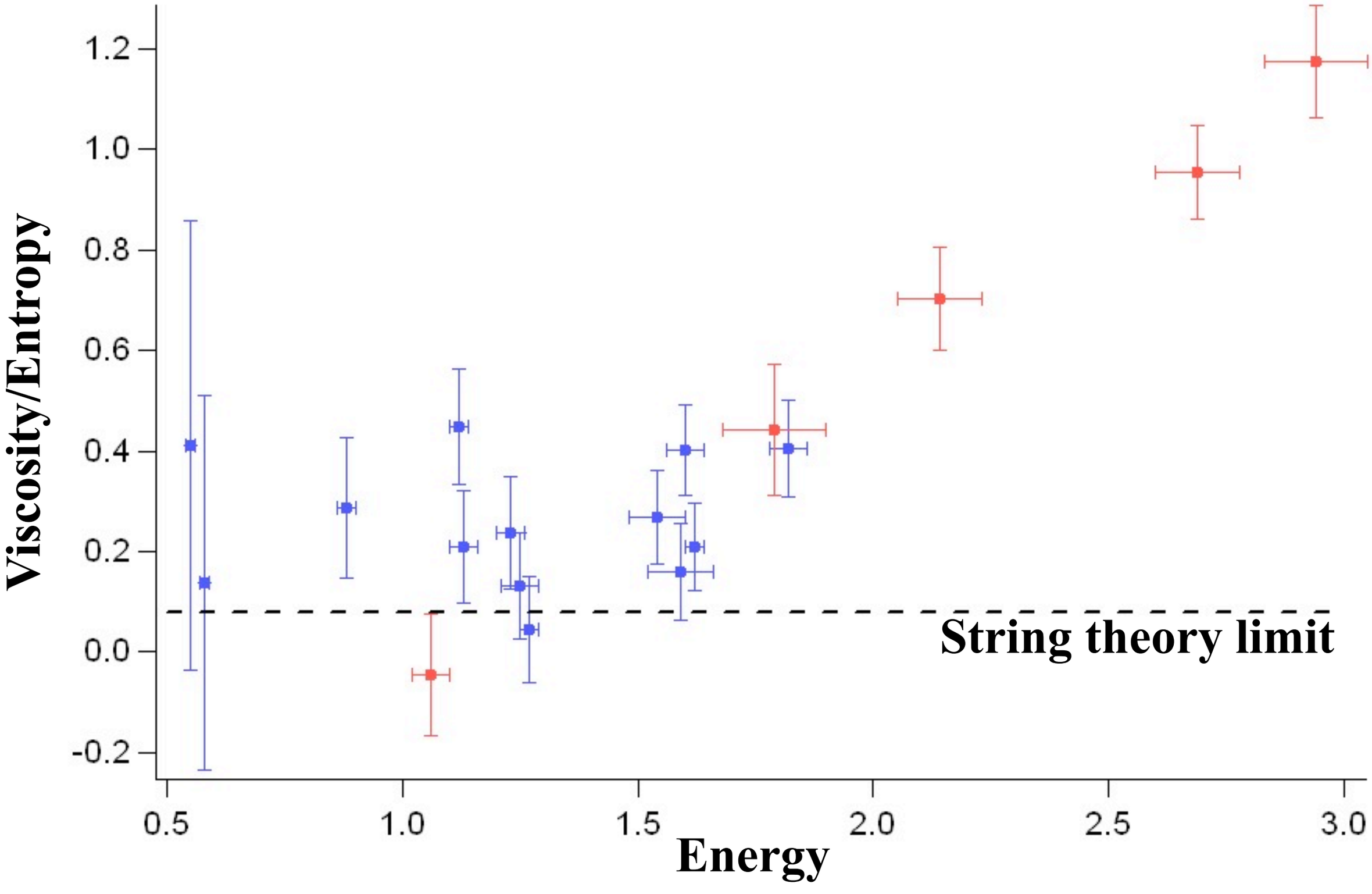

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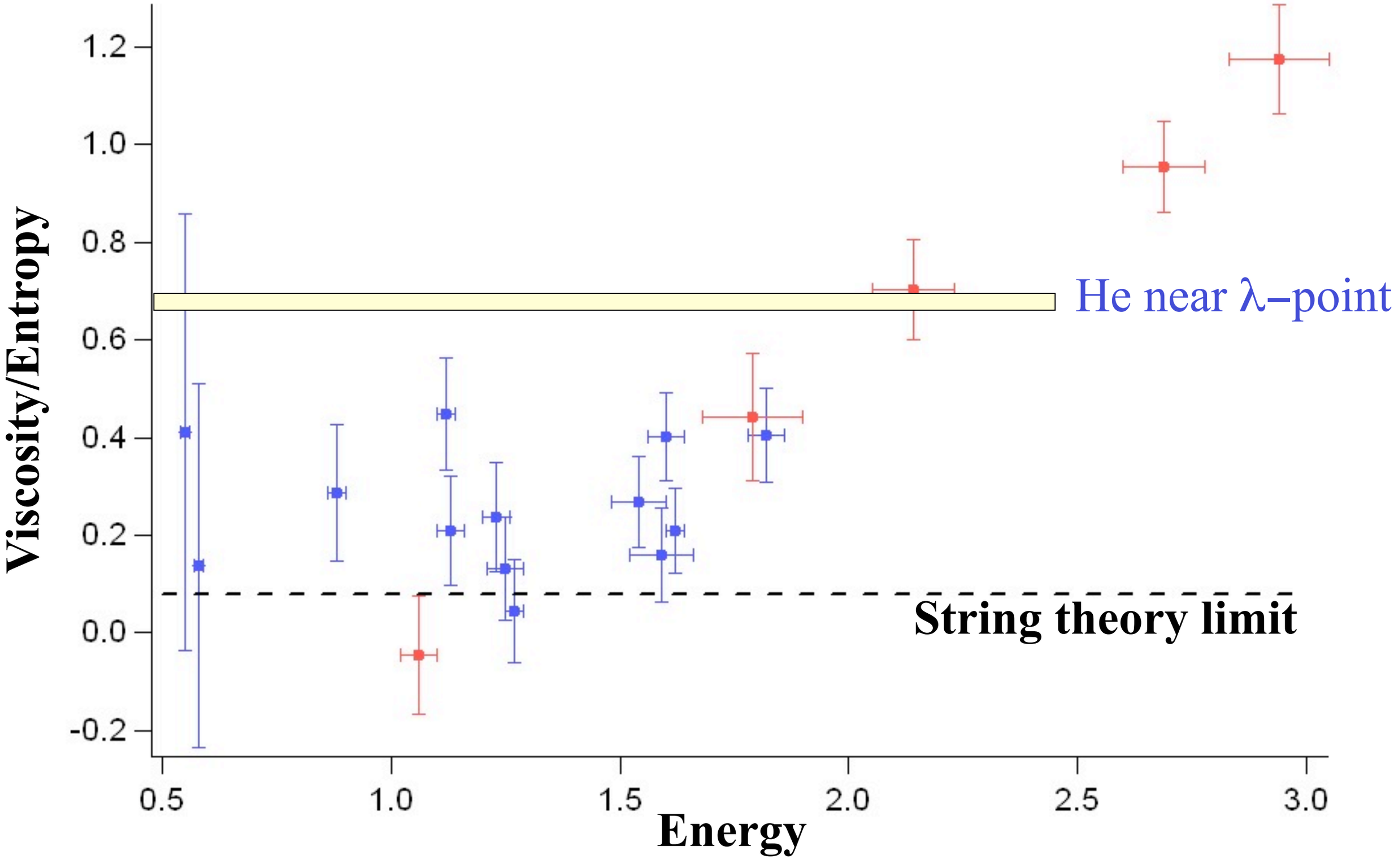

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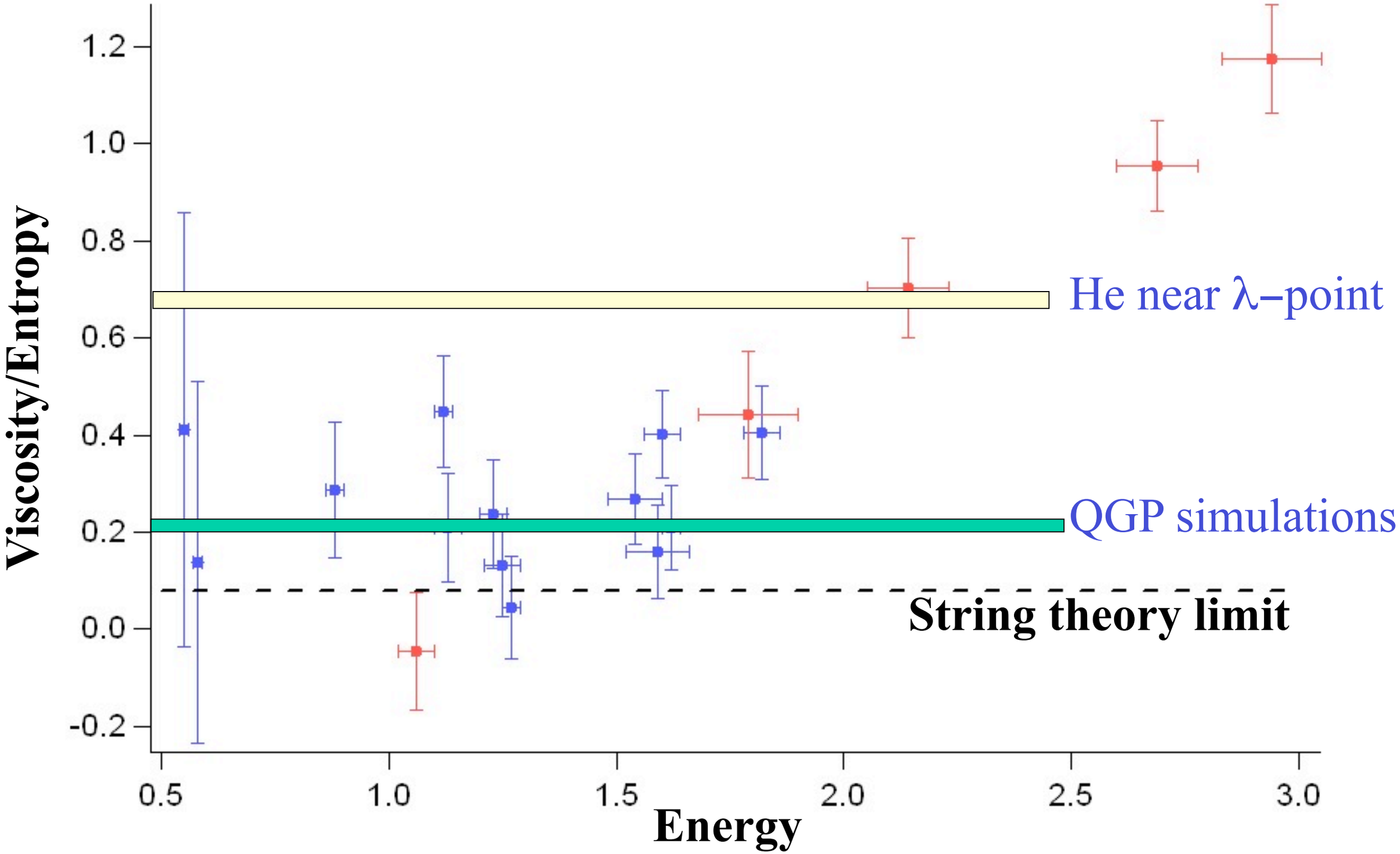

The 2008 Team

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Atom Cooling and Trapping

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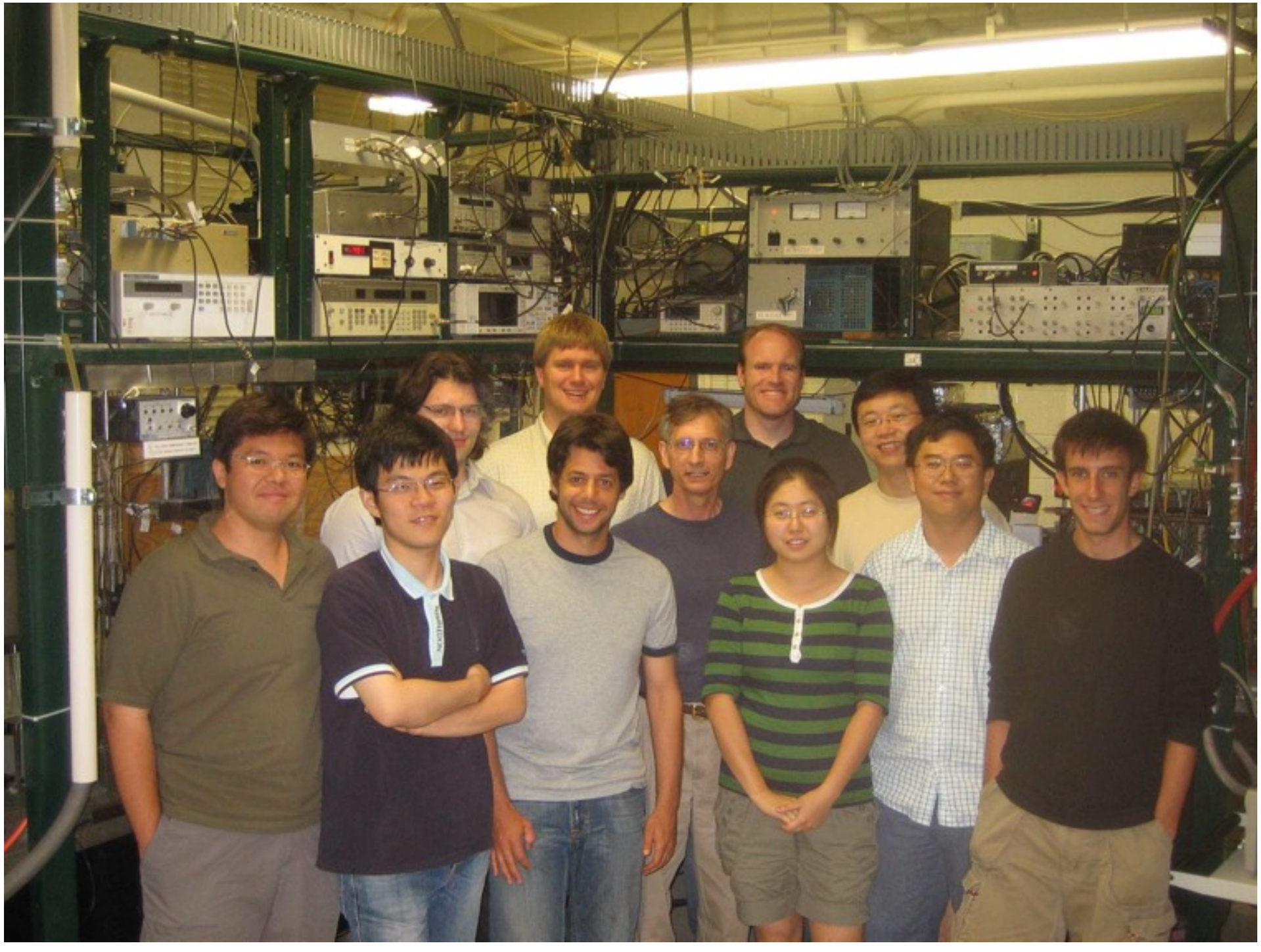

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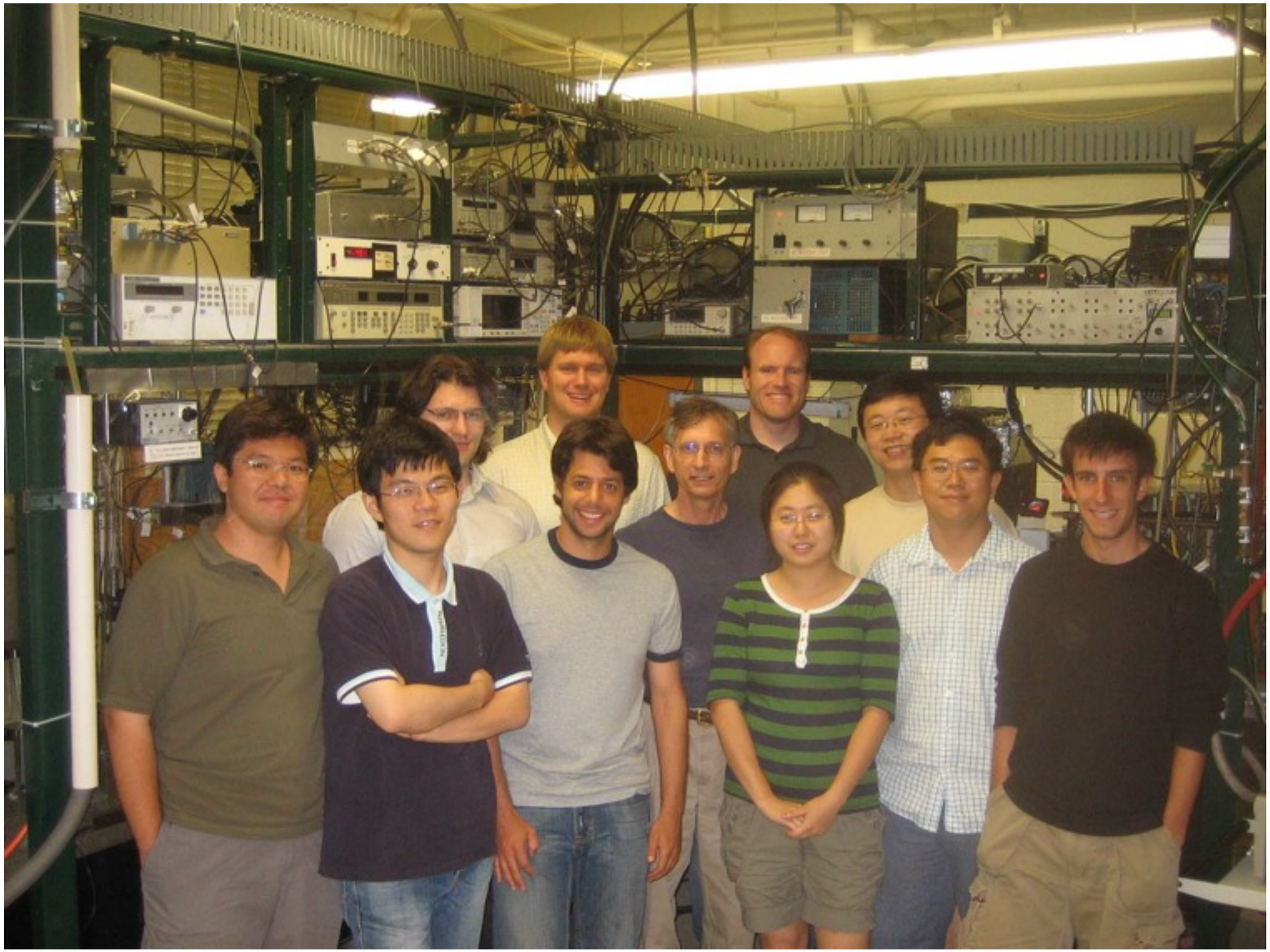

1st row:
Willie Ong
Chenglin Cao
James Joseph
Yingyi Zhang
Le Luo
Dave Weisberg

2nd row:
Ethan Elliot
John Thomas
Xu Du

3rd row:
Jessie Petricka
Bason Clancy